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"Analysis of Magnetometer Data/Wave Signals in the Earth's Magnetosphere"

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## I. Introduction

NASA grant NAG5-1325 was awarded to Augsburg College to support Mark Engebretson, Naiguo Lin, and a student in their continuing efforts in the reduction and analysis of Dynamics Explorer (DE) satellite magnetometer data at Augsburg College, with special emphasis on the ULF fluctuations and waves evident in such data. Work at Augsburg on the DE data set since April 1990 has been supported largely by this grant. Some work on DE data was also supported by a subcontract from Dr. Laurence Cahill, Jr. of the University of Minnesota, Co-Investigator for the DE magnetometer investigation.

As is typical for an undergraduate academic setting, much of the proposed work under this grant was done during the summer months, when both students and faculty have uninterrupted time to devote to these projects. Naiguo Lin left Augsburg July 1, 1991 for a similar position at the nearby University of Minnesota, but continued his involvement in study B below through submission of his manuscript in mid-August.

We list below both projects completed, with references to papers published or talks/posters presented, and projects which are incomplete or unfinished. Fortunately there are several of the former; unfortunately, there are also several of the latter. The DE magnetometer data set contains much that has not yet been analyzed thoroughly, if at all. It is thus important to continue working with it, and we hope to do so when time and/or funding allow.



## II. Scientific Accomplishments

### A. Studies of Pc 1 wave packets near the plasmapause

Dr. Engebretson cooperated with Drs. G. R. Ludlow and W. J. Hughes of Boston University and with Dr. J. A. Slavin of NASA/Goddard in an extensive comparative study of ion cyclotron waves using DE 1 magnetometer data and data from the ground-based Air Force Geophysics Laboratory magnetometer network. A paper based on this joint effort was published in 1991 [Ludlow et al., 1991].

Our contribution to this study was to check the DE 1 data for the presence of Pc 1 waves. Our first, cumbersome procedure was to transfer large, high time resolution MAF files to Augsburg, prepare color dynamic spectrograms, and scan them for evidence of pulsation activity in the 0.1— 2 Hz range. We later developed a much more efficient procedure which could be run on the DE696 computer at Goddard, thus no longer requiring the transfer of large amounts of data over SPAN to Augsburg. This system produced a summary black-and-white printer plot which gave enough information to judge whether or not pulsation activity was present in the DE 1 data. For a time these plots were produced regularly at Goddard and sent over the SPAN computer network for printout at Augsburg.

Dr. Engebretson also contributed to a continuing study by Dr. Laurence Cahill, Jr. of the University of Minnesota of Pc 1 pulsations observed by DE 1. The most recent results of this study were reported by Dr. Cahill at the fall 1989 meeting of the American Geophysical Union [Cahill et al., 1989].



## B. Satellite – ground pulsation study

While working as a postdoctoral scientist at NASA–Marshall Space Flight Center in Huntsville, Lee Reinleitner had identified a Pc 5 pulsation event in the DE–RIMS data set. Later, while he was a postdoctoral researcher at the University of Alaska, Lee found that ground magnetometer data from Alaskan and Canadian stations showed pulsation activity during the same time. Dr. Reinleitner assembled a set of data just as he was leaving Alaska, but he never pursued the investigation, and subsequently left the field of space physics. With the permission and cooperation of Dr. Reinleitner and Dr. John V. Olson, P.I. for the Alaska magnetometer chain, Naiguo Lin and Mark Engebretson continued this study (presented at the spring 1991 AGU meeting by Mark Engebretson [Engebretson et al., 1991]), which culminated in publication in the Journal of Geophysical Research [Lin et al., 1992].

The event described in this paper is one of the best examples showing the local resonance of individual field lines in the dayside magnetosphere. From 1630 to 1830 UT October 31, 1982 (82304) DE 1 traveled in the southern hemisphere from  $L \sim 10.3$  to  $\sim 4.3$ . Pulsation activity observed from the ground station at College, Alaska during this time showed a nearly constant frequency during much of the interval, while the activity at DE 1 clearly showed a frequency which increased with time (and decreasing  $L$ ), as is expected for pulsations with frequencies determined by local resonant conditions. Ground data were available from a number of additional stations at  $L$  values ranging from 17.5 to less than 4; where pulsations were observed, they all appeared to have frequencies consistent with local resonant conditions. In addition, superposed plots of the toroidal component of the satellite magnetic field and the radial component of the electric field showed that  $E$  and  $B$  were 90 degrees out of phase, as expected for a resonant standing wave.





Because the orbit of DE 1 remained at a nearly constant local time as it traversed such a wide range of L shells, this event provided an excellent case study of locally resonant Pc 4-5 oscillations. Naiguo Lin used both spectral and polarization analysis of the available magnetic field data and also incorporated PWI electric field data and RIMS particle data and ISEE 3 solar wind data in his study.

This study also showed the power of resonant pulsations to model flux tube plasma densities: calculated equatorial plasma densities based on the observed resonant frequencies at each L shell crossed by DE 1 compared reasonably well with densities observed by the RIMS thermal plasma detector, and indicated a radial density profile suggesting the presence of a gradual plasmopause falloff outside of an "inner plasmopause." Such a profile has found recent statistical support in the work of Horwitz et al. [1990], which found a variety of density falloff profiles instead of the commonly assumed "sharp" plasmopause profile.

#### C. Support for studies of ion energization processes

Dr. Engebretson has processed DE 1 magnetometer data in support of several dual-satellite studies of ion energization by broadband waves in the oxygen ion cyclotron frequency range.

The first study, using data from DE 1 and Viking, was led by Mats Andre of the University of Umea, Sweden. Bill Peterson of Lockheed is the primary DE scientist involved in interpreting the available data. Two papers were based on this first effort [Andre et al., 1990a,b], and Mats Andre also presented his findings at the spring 1990 meeting of the European Geophysical Society [Andre et al., 1990c].



We have prepared additional DE 1 magnetometer data for Bill Peterson for several related intervals, most of which have not led to fruitful studies. For each of several broadband wave events we prepared frequency spectra and color or black and white spectrograms, and as part of these efforts we have developed additional software for displaying sequential spectra.

We have also processed DE 1 magnetometer data in support of a study comparing DE 1 and Akebono (EXOS-D) observations of ion energization by broadband waves in the oxygen ion cyclotron frequency range January 28, 1990 (90028). Bill Peterson of Lockheed has taken the lead in this study [Peterson et al., 1993a]. Plots produced from the DE 1 magnetometer data have shown the same sort of broadband wave enhancement near the dayside cusp/cleft as had been reported in earlier papers produced in this collaboration.

We have continued some efforts to display and understand the magnetic field data obtained near 2000 UT January 28, 1990, during a near conjunction of DE 1 and Akebono (EXOS-D) in the vicinity of the dayside cusp. Analysis of the locations and relative timing appears to be crucial, as the cusp position determined by the two satellites is not the same. The most prominent feature in the DE 1 data between 1952 and 1953 UT is an unusual one, and is not at all characteristic of a static field-aligned current sheet or filament. This indicates that the feature is probably a time-dependent one, worthy of study in its own right. Dr. Cahill and Dr. Engebretson have seen several such unusual signatures in the magnetometer data near the auroral zone, but have never been able to successfully characterize them. This one is no exception; most likely the signature is caused by a beam of current strong enough to distort neighboring field lines, but multipoint observations would be needed to confirm this.



Standard techniques to deduce such currents from magnetometer signals are valid assuming the satellite crosses steady-state sheet currents; this assumption clearly appears to be violated at the start of the event of interest, but seems reasonable for later parts, such as from 1958 to 1959 UT, which are of at least as great scientific interest because they can be used to identify Birkeland current boundaries. Bill Peterson has interpreted this event instead as a standing Alfvén wave in a paper submitted to the Journal of Geophysical Research [Peterson et al., 1993b], which also was presented by Mark Engebretson at the NATO Advanced Research Workshop on Physical Signatures of Magnetospheric Boundary Layer Processes held May 10–14, 1993 near Oslo, Norway [Peterson et al., 1993c].

Some work will continue at a low level in support of further quantitative treatment of the magnetic and electric field data for this time period.

#### D. Search for Pc 1 wave events in 1981 DE 1 data

A copy of the first complete set of 1981 MAF files in spacecraft coordinates was provided to Augsburg in early summer 1991. In addition to providing some checks for data validity, it was our intention to search through these data sets for the presence of electromagnetic ion cyclotron waves, which had been identified on a few occasions in the early DE 1 data set using the University of Iowa Plasma Wave Instrument (PWI).

Our major contribution thus far was to find a data anomaly in the new MAF files, namely that fill data was written once every major telemetry frame (two minor frames) on all the early DE 1 data. (After mid-1984 spacecraft telemetry problems did indeed cause incorrect data values in minor frames 3 and 4, but before that time the data involved were correct.) We reported this to NASA Goddard staff, who identified and corrected the software error responsible.



Our method of searching involves producing color Fourier spectrograms of the highest resolution DE 1 data (using a computer workstation) and then visually inspecting them for organized wave activity above the noise background. Despite the many hours spent on this project, the compute-intensive nature of this effort resulted in our being able to search only the first three months of 1981 DE 1 data. Other than the one known event on day 81296, no other Pc 1 events were detected in the 1981 data we had time to cover. We purchased a much faster computer workstation in May 1993, and if time permits we will continue this effort in the future with the remainder of the DE 1 data available to us. Unfortunately, this means that we could not finish this study by the time funding ended.

A byproduct of this search through the 1981 DE-1 data was to look for evidence of the electrostatic or electromagnetic character of the events studied by Dr. Janet Kozyra of the University of Michigan. One of her few events was clearly present in our data, and so is electromagnetic (the event occurring on 81296). We have processed far enough to cover the time of most of her list of events, and found no evidence for wave activity in the MAG data for any of the other events: this suggests the waves are electrostatic, not electromagnetic.

#### E. Study of Pc 3-5 events observed simultaneously by DE 1 and by AMPTE CCE.

Our original proposal indicated our intent to compare DE 1 data with data in hand at Augsburg from Antarctic ground stations and from the AMPTE CCE satellite for selected periods in 1984 and 1986. We obtained a sizeable amount of DE 1 data from fall 1984, selected for times when (predominantly) radially polarized Pc 4 pulsations were observed at AMPTE CCE, and from spring 1986, selected for times when azimuthally polarized, harmonically structured Pc 3 pulsations were observed at AMPTE CCE. Unfortunately, DE 1 was seldom operated in locations roughly conjugate to AMPTE CCE.





Using the books of "conjunctions" between DE 1 and AMPTE CCE generated by Bill Peterson of Lockheed, we searched in June and July 1992 for times when these two satellites were on or near the same field line and interesting long-period ULF wave activity was observed at AMPTE CCE. (A complete set of Fourier spectrograms of ULF wave activity for the AMPTE CCE mission was produced at Augsburg. These spectrograms were used to identify ULF wave activity at AMPTE CCE.) After identifying over 50 such cases, we cut down the list to a high priority set of ten events and forwarded the list to NASA/Goddard personnel. DE 1 data could be processed at this time for seven of these ten events, and was received in September and October 1992. We are now beginning to compare the vector data from the two satellites for the seven good events. This project too was left incomplete at the end of the period of grant support, and will be picked up by students during summer 1993 if time and staffing permit.

#### F. Support for studies of electromagnetic transients on DE 1

We checked five events studied by Vikas Sonwalkar of Stanford, who noted high frequency electric and magnetic noise using the Stanford antennas, and we found no evidence of abnormal variations in the MAG data during any of these five events. We prepared line plots and spectrograms of each event and forwarded them to Dr. Sonwalkar for his interpretation. The MAG data suggest that either the noise bursts were related to characteristics of the PWI instrument, that they represent discharges nearer the satellite (hence away from the MAG boom), or that their amplitude is for some reason too low, or their time duration too short, to register in the MAG data.

Because of the bad points associated with telemetry fill in these five events (all late in the DE mission), it is still possible that in each case the noise spikes occurred during times when the MAG data was not transmitted. It is



unlikely that such would be the case for all five events, however.

#### G. Analysis of wave events induced by sudden impulses

We assembled data from a variety of locations in space and on the ground for the study of an SI event which occurred October 9, 1984. A preliminary report on our observations was presented at the Fall 1989 meeting of the American Geophysical Union [Engebretson et al., 1989]. Although we first noticed this event at AMPTE IRM in the near-equatorial magnetosheath, consequent pulsation signatures were found at synchronous orbit (GOES 5 and 6) and impulsive magnetic field changes (but no magnetic pulsations) were evident at AMPTE CCE. We subsequently noted that DE 1 was situated near the sunward edge of the polar cap, thus providing a rarely seen perspective on the global magnetospheric consequences of an SI. Although it also did not note a pulsation signature clearly associated with the SI, the field magnitude changed in a manner consistent with the passage of a field compression past the satellite at 1247 UT. Of perhaps greater interest was the observation by the DE 1 EICS instrument of an intense beam of protons traveling upward from the ionosphere a few minutes after the onset of the compression. We are investigating the relation between this beam and the compression.

A study of another sudden compression and its associated pulsation phenomena was completed during this period [Cahill et al., 1990], but the work done by Drs. Lin and Engebretson on this paper was supported by funds provided earlier to Dr. Cahill, not by this grant.



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PREV. ANN  
73A 10307Field and Thermal Plasma Observations of ULF Pulsations  
During a Magnetically Disturbed IntervalN. LIN,<sup>1,2</sup> M. J. ENGBRETSON,<sup>1</sup> L. A. REINLEITNER,<sup>3</sup> J. V. OLSON,<sup>4</sup> D. L. GALLAGHER,<sup>5</sup>  
L. J. CAHILL, JR.,<sup>6</sup> J. A. SLAVIN,<sup>7</sup> AND A. M. PERSOON<sup>8</sup>

ULF pulsations were observed by DE 1 between 1600 and 1830 UT, October 31, 1982, during a magnetically disturbed interval. Ground observations suggested that the pulsations were excited by a sudden increase in the solar wind velocity and pressure. During the pulsation interval DE 1 traveled near apogee from  $-55$  to  $-20^\circ$  geomagnetic latitude and from  $L \sim 13$  to  $L \sim 4$  at about 0900 LT. The waves observed were azimuthal oscillations preceded by gradually decaying long period compressional waves which lasted for more than 1 hour. Phase relations between magnetic and electric field oscillations and calculated Poynting flux indicate that in the outer magnetosphere ( $L > 8$ ) DE 1 observed propagating waves which contained strong poloidal components, while the quasi-sinusoidal toroidal waves seen later for  $L < 10.3$  were standing along field lines. The toroidal waves appeared as four wave packets, each of which corresponded to a region with a distinct plasma distribution. The observed wave periods decreased with  $L$  over an extended magnetospheric region. The seemingly weak interaction between magnetic shells suggests that the source was a broadband one. Magnetometer data from several high latitude observatories located near the footpoints of the magnetic shells crossed by DE 1 were also examined. The magnetic pulsations on the ground contained many frequency components, and the waves seen most strongly in space were often not the strongest signals seen on the ground near the same field lines. The broadband nature of the ground pulsations indicates that the stations also detected oscillations of the adjacent field lines. The major frequencies seen at ground stations seemed to be roughly constant for about 2 hours but  $L$  dependent. This suggests that the changing periods seen in space by DE 1 were clearly  $L$  related and not temporally varying.

## INTRODUCTION

ULF pulsation studies have been very helpful in understanding the processes of basic plasma physics in the magnetosphere. Analysis of these waves has revealed important aspects of energy coupling between the solar wind and the magnetosphere and ionosphere. Earlier work [cf. *Chen and Hasegawa*, 1974; *Southwood*, 1974], proposing that surface waves on the magnetopause excite field line resonances in the magnetosphere, has been widely applied to interpretation of observed long period (above 10 s) ULF wave phenomena. In recent years, continuing efforts have been made to solve the problem of mode coupling between externally excited compressional waves and magnetospheric field line resonances [e.g., *Kivelson and Southwood*, 1986; *Zhu and Kivelson*, 1988; *Lee and Lysak*, 1989, 1990; *Allan et al.*, 1986]. Spacecraft observations have provided further evidence of toroidal oscillations of resonant field lines occurring throughout the dayside magnetosphere [*Engbreton et al.*, 1986b; 1988; *Takahashi et al.*, 1988; *Anderson et al.*, 1990; *Cahill et al.*, 1990; *Zanetti et al.*, 1987]. AMPTE CCE observations of the dayside outer magnetosphere [cf. *Engbreton et al.*, 1986a] dis-

played an essentially continuous variation in resonant period as a function of  $L$ , implying that adjacent  $L$  shells can oscillate in the azimuthal direction with very little interaction.

In exploring the external source of long-period ULF waves (in the Pc 3 to 5 range), the long-proposed Kelvin-Helmholtz instability at the magnetopause has been further investigated [*Pu and Kivelson*, 1983, and the references therein; *Miura*, 1987; *Ogilvie and Fitzenreiter*, 1989] and more observational evidence favoring the mechanism was found [e.g., *Potemra et al.*, 1988; *Muchelletal.*, 1990; *Anderson et al.*, 1990]. Recently, more attention has been paid to the role of the variation of the solar wind dynamic pressure in generating ULF waves in the magnetosphere [*Song et al.*, 1988; *Sibeck et al.*, 1989; *Potemra et al.*, 1989; *Southwood and Kivelson*, 1990]. Harmonic Pc 3,4 waves in the outer dayside magnetosphere associated with a quasi-parallel geometry at the subsolar bowshock have also been reported [*Engbreton et al.*, 1987, 1991; *Lin et al.*, 1991]. They found that, in addition to ever strong evidence that small solar wind cone angles favored the occurrence of the harmonic pulsations, disturbances of magnetic field which contained significant transverse fluctuations and energized turbulent plasma in the subsolar magnetosheath correlated closely with the harmonic oscillations in the magnetosphere.

Multi-instrument and multipoint observations have more and more been used in pulsation studies. The use of particle data and electric field data as well as magnetic measurements is vital in determining wave modes, wave propagation, and other properties of the waves [e.g., *Cahill et al.*, 1986; *Takahashi et al.*, 1988; *Potemra et al.*, 1989]. *Waite et al.* [1986], using particle detector and electric field measurements, revealed the drift motion of the plasma near resonant field lines in a Pc 5 event. *Lin et al.* [1988] using a multichannel energetic ion detector determined the propagation of Pc 5 waves in both the radial and the azimuthal direction. In this study we have used particle and electric and magnetic field measurements from the DE 1 spacecraft to investigate a pulsation event. The polar orbit of DE 1 has been utilized to observe wave structure along field lines and across field lines [*Cahill et al.*, 1984, 1986; *Lin et al.*, 1986; *Engbreton et al.*,

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1986b]. Some of the observations were made a few tens of degrees away from the magnetic equator [cf. Cahill *et al.*, 1986], covering a region infrequently observed in comparison with the near equatorial region. The event reported here was observed in space covering a large range of  $L$  shells (from  $L \sim 13$  to  $L \sim 4$ ) and magnetic latitudes (from  $\sim -55^\circ$  to  $-19^\circ$ ). The spacecraft observations are then compared with ground observations near the footprint of the DE 1 trajectory during the period.

### DE 1 ORBIT AND INSTRUMENTATION

DE 1 magnetic field data presented here were taken by a three-axis flux gate magnetometer on board the spacecraft [Farthing *et al.*, 1981]. The data were originally recorded at 16 vector samples per second, but we used 6-s averages of the data in this paper. Electric field measurements were obtained with the University of Iowa plasma wave instrument (PWI), which has two 100-m probes perpendicular to the spin axis and a 9-m double probe along the spin axis [Shawhan *et al.*, 1981]. Particle measurements from DE 1 were obtained by the retarding ion mass spectrometer (RIMS) [Chappellet *et al.*, 1981]. Three nearly identical ion mass spectrometers of the RIMS instrument are denoted +Z (pointing west), -Z (pointing east), and RL (pointing radially outward), respectively. The radial head (RL) rotates in the spin plane and is perpendicular to the spin axis which is pointing east.

The wave event was observed by DE 1 between 1600 and 1830 UT October 31 (day 304), 1982. (The pulsations might have started earlier, but no DE 1 data are available for several hours before 1600 UT.) During the interval, DE 1 was traveling near apogee between 0912 MLT,  $-55^\circ$  geomagnetic latitude at 1600 UT, and 0836 MLT,  $-19.1^\circ$  geomagnetic latitude at 1830 UT. It reached apogee at about 1652 UT. The trajectory of the DE satellite during the 3-hour interval is sketched in Figure 1 which is plotted by rotating the meridian planes that DE 1 crossed during the event onto a meridian plane on the paper.

### SOLAR WIND AND GEOMAGNETIC CONDITIONS

The day of the observations is recorded as the third most disturbed day of the month ( $K_p$  indices of the day are 4-, 4+, 3+, 1-, 4+, 4, 6+,

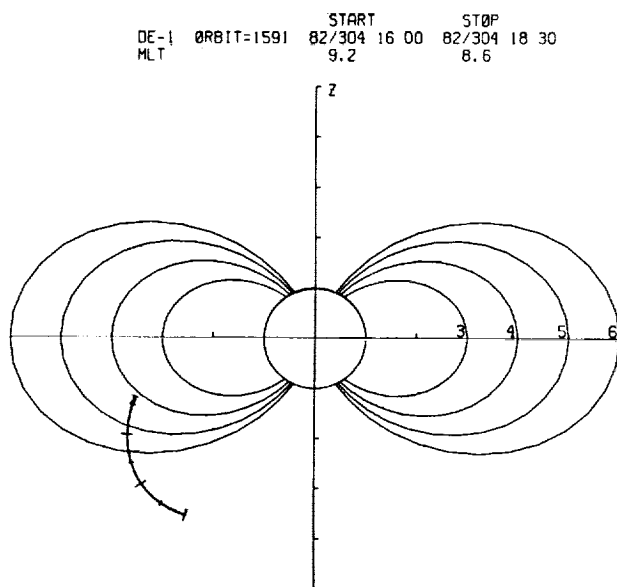


Fig. 1. The trajectory of DE 1 from 1600 UT to 1830 UT, October 31, 1982, plotted by rotating the meridian planes that DE crossed during the event onto a meridian plane on the paper.

5). Solar wind data measured from ISEE 3, which was approximately at GSM coordinates  $(-100, -75, 38)$  tailward of the Earth at 1600 UT, are displayed in Figure 2a for the magnetic field  $B_x$ ,  $B_y$ ,  $B_z$ , and the total magnetic field in GSM coordinates and Figure 2b for plasma bulk velocity, density, and temperature. Figure 2a shows that at about 1345 UT there was a sharp increase in the magnetic field magnitude from  $\sim 8$  nT to  $\sim 20$  nT. At the same time, the solar wind velocity also increased sharply from  $\sim 500$  km/s to  $\sim 700$  km/s, and remained at a high level until the end of the day (Figure 2b). The velocity increase was accompanied by sudden increases in the plasma density and temperature. The above changes in plasma parameters at 1345 UT implied a sudden increase in the solar wind pressure, which, as will be shown later, initiated magnetic pulsations observed on the ground.

At  $\sim 1500$  UT the solar wind magnetic field turned southward. There was probably another dramatic change in the solar wind parameters at about 1530 UT, accompanying a northward turning of IMF  $B_z$ . Unfortunately, there are data gaps between 1522 UT and 1545 UT in both magnetic field and plasma data. Comparison of the plasma data before and after the gap, however, shows that fluctuations of the solar wind velocity, density, and temperature and thus the solar wind dynamic pressure intensified during the gap period. We will show later that this intensification of the variation of the solar wind dynamic pressure is coincident with the occurrence of a negative bay in the  $H$  components of some ground stations and an intensification of magnetic pulsations on the ground.

At  $\sim 1700$  UT the solar wind magnetic field started to rotate its direction from originally northward and slightly downward ( $-B_y$ ) to duskward and gradually southward. At  $\sim 1750$  UT,  $B_z$  became negative. This southward turning of  $B_z$  is probably associated with the substorm signatures observed at about 1800 UT at some ground stations.

### DE 1 MAGNETIC FIELD OBSERVATIONS

Figure 3a shows the difference between DE 1 measurements of the magnetic field from 1600 UT to 1900 UT and the Magsat model field [Langel *et al.*, 1980] in three components of a spherical coordinate system:  $dB_r$  points radially outward,  $dB_\theta$  points southward, and  $dB_\phi$  points eastward. The  $dB_\phi$  component was negative during the entire 3-hour interval, indicating that the magnetic field lines were bent westward, or tailward, since DE 1 was at about 0900 local time. The positive  $dB_\theta$  component throughout the interval indicates field lines at DE 1 were stretched outward and oriented more southward than usual. The large increase in the  $dB_\theta$  component starting at about 1740 UT was probably caused by the southward turning of IMF  $B_z$  observed by ISEE 3 at 1750 UT. In the subsolar magnetosheath this southward turning of  $B_z$  was observed by ISEE 1 and 2 at  $\sim 1737$  UT (M. Cao, private communication, 1991).

In order to examine the compressional and transverse components of magnetic pulsations we rotate the magnetic field data used in Figure 3a into a field-aligned coordinate system with orthogonal unit vectors  $\hat{\mu}$ ,  $\hat{v}$ ,  $\hat{\phi}$ . The vector  $\hat{\mu}$  is parallel to the background magnetic field,  $\mathbf{B}_0$ , which is defined as the 151-point (906 s) running average of the original data, and thus  $\hat{\mu} = \mathbf{B}_0 / |\mathbf{B}_0|$ . The azimuthal component  $\hat{\phi} = \hat{\mu} \times \hat{r} / |\hat{\mu} \times \hat{r}|$ , where  $\hat{r}$  is the radial unit vector in spherical coordinates and the transverse poloidal component  $\hat{v} = \hat{\phi} \times \hat{\mu}$ . Figure 3b displays the variation of the magnetic field projected to the above coordinates,  $b\mu$ ,  $bv$ ,  $b\phi$ .

Figure 3b shows that before 1715 UT, compressional oscillations with decaying amplitude were seen in  $b\mu$ . The period of the compressional waves was not constant. It decreased with  $L$  values from  $\sim 700$  s to  $\sim 450$  s as DE 1 travelled inbound from  $L \sim 13.3$  to 7.5. Between

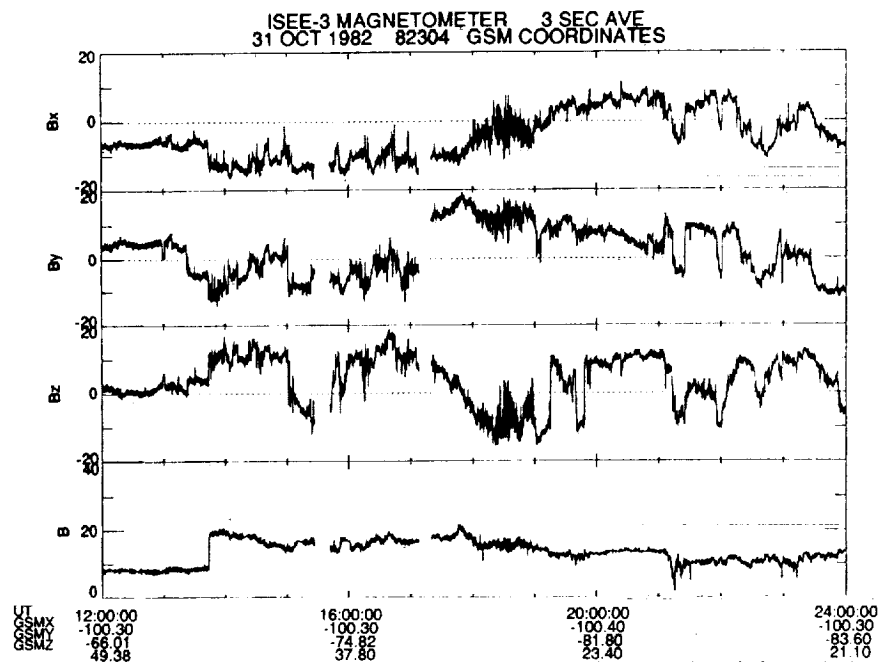


Fig. 2a. Solar wind magnetic field data measured from ISEE 3:  $B_x$ ,  $B_y$ ,  $B_z$  and the total magnetic field in GSM coordinates.

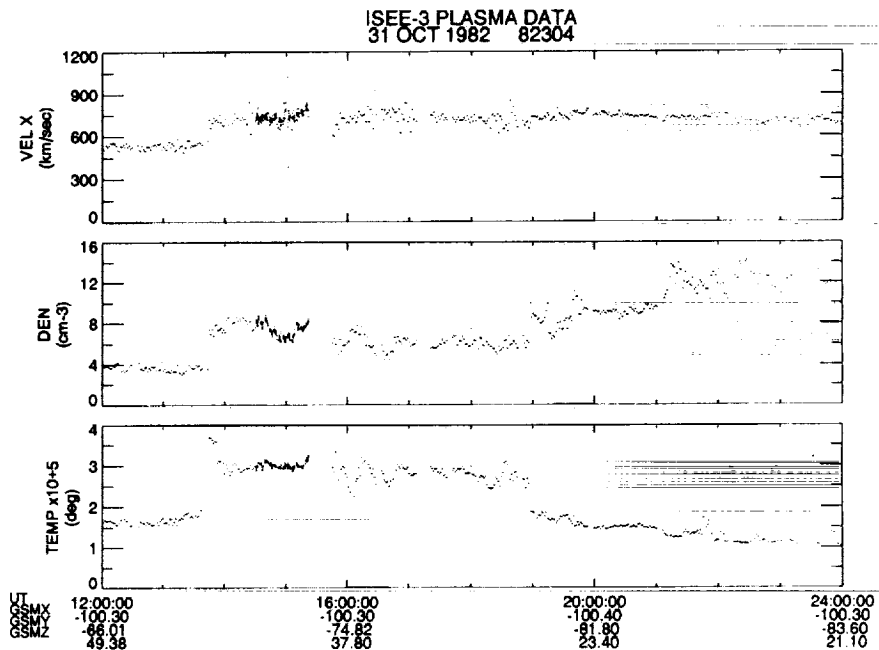


Fig. 2b. Solar wind plasma data measured from ISEE 3: plasma bulk velocity, density, and temperature.

1605 and 1630 UT, as DE 1 travelled from  $L \sim 12.6$  to 10.3, a 110-s poloidal wave with a maximum amplitude of about 5 nT was seen mainly in the  $b_v$  component before 1620 UT. After 1630 UT the observed magnetic pulsations were mainly in the azimuthal component,  $b_\phi$ . The wave period clearly decreased from  $\sim 400$  s at 1630 UT ( $L = 10.3$ ) to  $\sim 150$  s at 1820 UT ( $L = 4.7$ ) as the spacecraft moved to lower  $L$  shells. The azimuthal waves may roughly be divided into four wave packets: 1630 - 1700 UT, 1700 - 1740 UT, 1740 - 1805 UT, and 1805 - 1820 UT. A summary of Fourier analyses of subintervals of the 3-hour data is shown in Table 1. Note that although Fourier

transforms for each subinterval give a certain value of peak frequency for each component, the real frequency in a wave packet may still vary with  $L$ . In some subintervals (for example, the one from 1630 to 1700 UT) the wave frequency varies significantly, so that the calculated frequency for the interval has little meaning. The polarization of the waves on the  $v$ - $\phi$  plane is listed in the last column of Table 1. Except for the transverse waves between 1630 and 1700 UT (2.2 - 5.0 mHz) which exhibited alternately left-handed and right-handed polarization, long-period transverse waves ( $T > 100$  s) in other subintervals were left-handed or linearly polarized.

TABLE 1. Summary of Magnetometer Observations of DE 1

Time Period, UT	<i>L</i>	GM latitudes deg	Wave Frequency, mHz	Main Components	Polarization <i>bv-bφ</i>
1600–1700	13.3–8.3	–55.0––41.4	1.5–2.9	<i>bμ</i>	
1600–1630	13.3–10.3	–55.0––48.0	9.1	<i>bv</i>	left
1630–1700	10.3–8.3	–48.0––41.4	2.2–5.0	<i>bφ</i>	left-right
1700–1740	8.3–6.4	–41.4––32.6	3.9	<i>bφ</i>	left
1740–1805	6.4–5.3	–32.6––26.4	3.9	<i>bφ</i>	linear
1805–1820	5.3–4.7	–26.4––22.2	6.5	<i>bφ</i>	left
1820–1840	4.7–4.0	–22.2––15.7	37.0	<i>bφ</i>	

#### PARTICLE SIGNATURES OBSERVED BY THE RIMS INSTRUMENT

Plate 1 shows proton count rate measurements from the radial head of the RIMS instrument in a spin angle versus time spectrogram format. The dashed line in each panel indicates the angle at which the look direction of the instrument is parallel to the measured magnetic field, while the dotted line indicates the antifield direction. Zero degree ram angle in the plots means that the radial detector is viewing into the direction of motion of the spacecraft.

The first panel of Plate 1 shows that at about 1606 UT the radial head of the instrument observed a transition from unidirectional flow out of the southern hemisphere (count rate enhancements along the dotted line before ~ 1606 UT) to gradually increasing bidirectional flow after 1606 UT ( $L \sim 12.5$ ). Data (not shown) from the DE 1 energetic ion composition spectrometer (EICS), courtesy of W. K. Peterson, indicated clear signatures of alpha particles before 1607 and none thereafter. These observations indicated that DE 1 probably moved from open field lines to closed field lines. The bidirectional flow was not symmetric, however, with the flow streaming away from the southern ionosphere apparently stronger than the one in the opposite direction. The asymmetric flow after 1606 UT is commonly seen when the spacecraft is well into the southern hemisphere (DE 1 was between  $-53.5^\circ$  and  $-42.7^\circ$  geomagnetic latitude from 1606 UT to 1654 UT), and the further into the southern hemisphere the stronger the flux may appear from the southern ionosphere than the northern ionosphere. After 1654 UT, the fluxes parallel and antiparallel to the magnetic field apparently became equally strong. However, we note that, since the flow from the northern hemisphere is closer to the ram direction than the plasma flow from the southern hemisphere, the observed antifield flow will be artificially enhanced. Thus it is possible that the bidirectional flow remained asymmetric after 1654 UT.

The magnetic signature which coincided with the transition seen at ~ 1606 UT in the plasma data was the beginning of the 110-s poloidal oscillation in the *bv* component. In fact, the plasma data also show the 110-s wave signature between 1606 and 1620, which appears as a fluctuation in the pitch angle of the otherwise field-aligned outflowing hydrogen ions. The above proton signature was probably caused by the oscillation of field lines in the poloidal direction. The compressional wave in *bμ* at the beginning of the interval seemed to start at about the same time, too, since a large amplitude of the compressional wave was seen after ~ 1605 UT. Unfortunately, no DE 1 data are available before 1600 UT to confirm this.

At ~ 1742 UT and ~ 1749 UT the RIMS instrument observed two brief periods of isotropic ion fluxes with slightly larger intensity, each lasting for only 1 to 2 min. This might suggest that DE 1 encountered detached plasmaspherelike plasma. At ~ 1753 UT ( $L \sim 5.8$ ), DE 1 encountered a rammed hydrogen distribution characteristic of the plasmasphere. The magnetic signature that is coincident with the entering of the spacecraft into the plasmasphere is the

transition between two wave packets from 1740 UT to 1750 UT which can be clearly seen in the *bφ* component. Note that the transition time is also coincident with the time when  $dB\theta$  began to increase (Figure 3a), which is probably associated with the southward turning of the interplanetary magnetic field (IMF) and magnetosheath magnetic field. It seems that the southward turning made the field lines at the location of DE 1 tilt more southward so that DE 1 encountered the plasmopause region at that time. The waves seen on both sides of the plasmopause (the waves before and after 1740 UT) are similar: they are mainly in the azimuthal component and have a period of about 256 s. The amplitude of the waves inside the plasmasphere (~ 5.5 nT) is slightly larger than outside (~ 4 nT), and the inside waves are linearly polarized while the outside ones are left-hand polarized.

From ~ 1753 UT to ~ 1814 UT the RIMS instrument observed a series of quasi-periodic enhancements of ion densities near the ram direction (see the second and third panel of Plate 1). The corresponding magnetic signature during this interval is the development of two wave packets in *bφ*: one occurred between 1750 UT and 1805 UT, and the other started at ~ 1805 UT, reached its maximum (~ 8 nT) at ~ 1815 UT, and then decayed rapidly.

#### DE 1 ELECTRIC FIELD MEASUREMENTS

The DC electric field data for the event are available for the interval between 1600 UT and 1812 UT in three components: *Epar* and *Eperp*, which are the spin-plane field components parallel and perpendicular to the projection of the magnetic field vector in the spin plane, respectively, and *Ez*, which is the average component of the DC electric field along the spin axis. The DC output is sampled at 16 samples per second. Computations are performed with segments of the DC data spanning 6 s of time (one spin period). These data segments are "centered" on times which are 4 s apart, so there is a 2-s overlap between segments. In this event the parallel, perpendicular, and +z directions in electric field measurements correspond to +μ, +ν, and -φ in the field-aligned coordinates we have used to present the magnetic field data.

To see the variation of the wave electric field, we have high-pass filtered the data by subtracting the running average over about 900 s from the original data. We then compared the *E* field variation with the magnetic variation. Field line oscillations in the azimuthal direction (*bφ*) result in the variation of the electric field in the transverse component (*Eperp*) in the magnetic meridian plane where the oscillating field line is located. The poloidal oscillation (*bv*) produces electric field variations in the azimuthal direction (*Ez*).

In Figure 4 we compare the toroidal component *bφ* (solid lines) with *Eperp* (dashed lines). This figure shows that between 1630 UT and 1655 UT, when DE 1 was in the outer magnetosphere ( $L > 8.5$ ), higher-frequency (less than 1-min period) variations in *Eperp* were seen superimposed on the long-period waves (200 - 450 s) which were also clearly seen in *bφ*. Between 1700 UT and 1735 UT, when

## DE 1 RIMS Data (Radial Head) 82/304 31 Oct. 1600–1900 UT

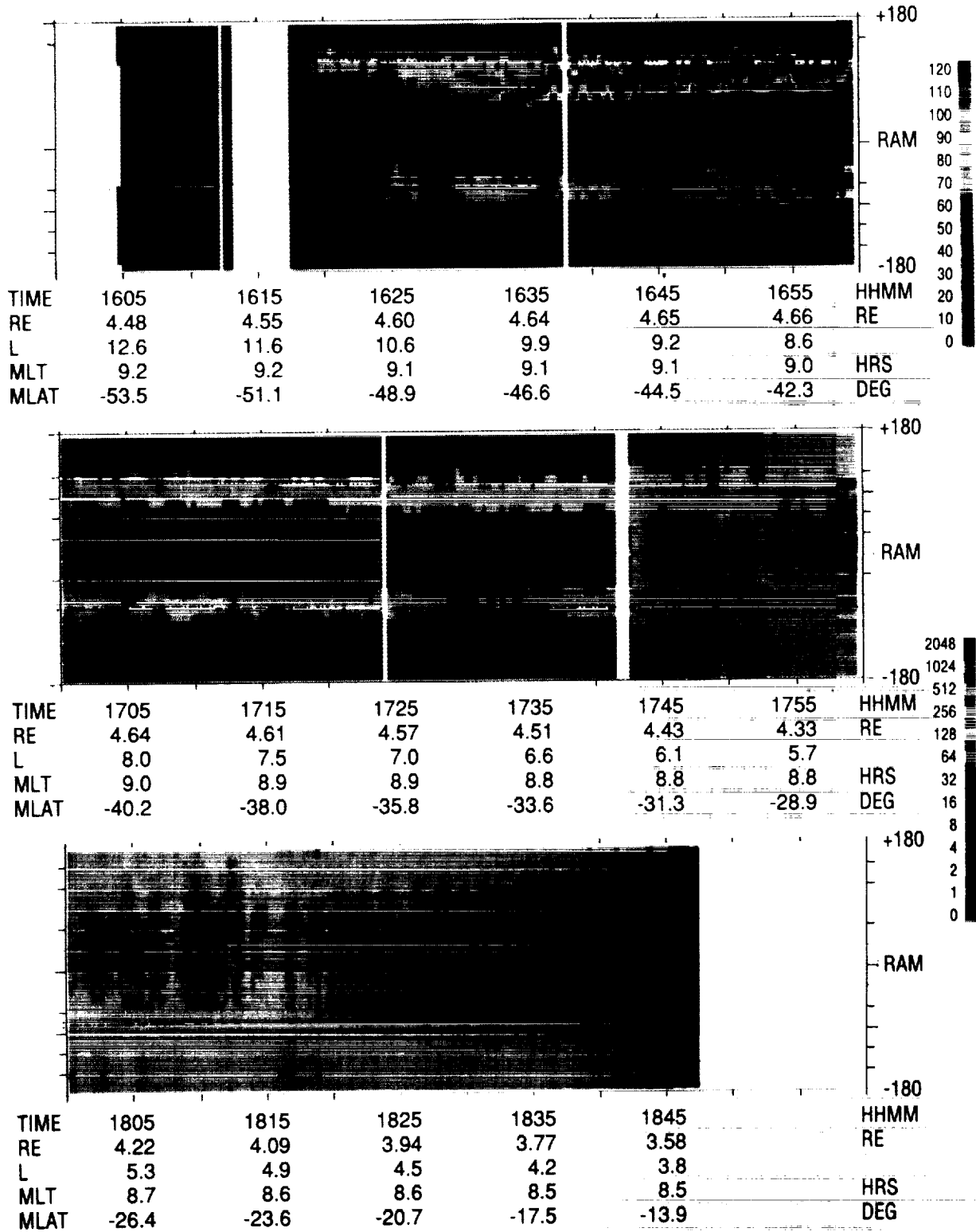


Plate 1. Proton count rate measurements from the radial head of the DE 1 Retarding Ion Mass Spectrometer (RIMS). The dashed line in each panel indicates the look direction of the instrument which is parallel to the measured magnetic field, while the dotted line indicates the antfield direction. Zero degree ram angle in the plots means that the radial detector is viewing into the direction of motion of the spacecraft.

there were strong oscillations in  $b\phi$  (about 250 s in period and a maximum amplitude of about 5 nT), Eperp was very weak (almost zero). At about 1748 UT the variation of Eperp intensified to an amplitude of about 1.5 mV/m and remained in quadrature with

magnetic pulsations in  $b\phi$ . Actually, the 90 deg phase shift between  $b\phi$  and Eperp with  $b\phi$  leading Eperp can be seen for the transverse oscillations after 1630 UT, even during the interval when electric pulsations were weak. This phase relation between  $b\phi$  and Eperp

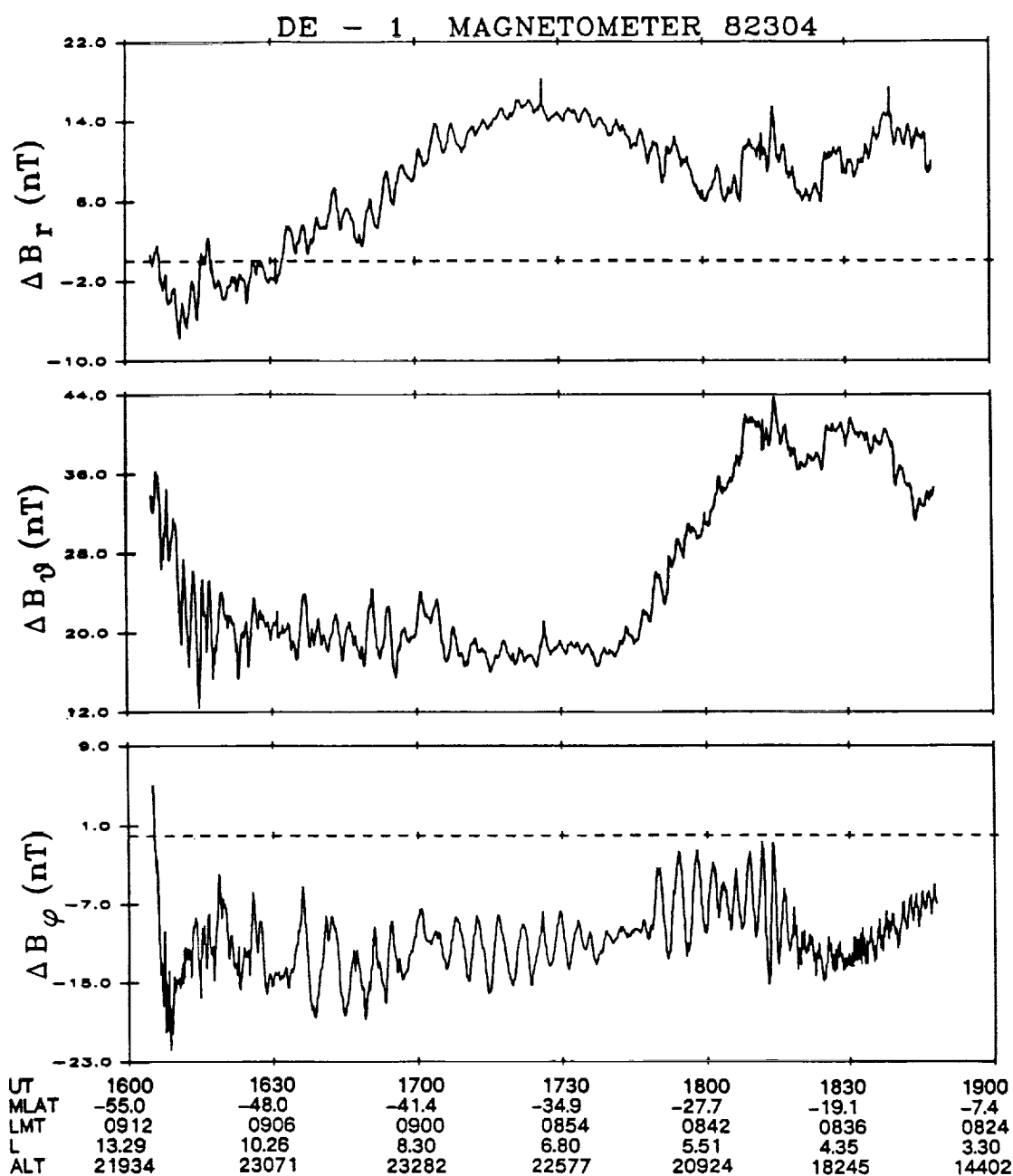


Fig. 3a. The difference between DE 1 measurements of the magnetic field and the Magsat model field in three components of a geomagnetic spherical coordinate system:  $\Delta B_r$  points radially outward,  $\Delta B_\theta$  points southward, and  $\Delta B_\phi$  points eastward.

suggests that the transverse waves were standing Alfvén waves along magnetic field lines.

The short tubular  $E_z$  antenna often detects spacecraft-generated noise which enhances the signal detected by the  $E_z$  antenna. Although the  $E_z$  amplitude values are contaminated, the high-pass-filtered  $E_z$  data (not shown) show a component remained which oscillated in antiphase with the  $b_v$  component before 1655 UT, especially between 1605 UT and 1620 UT, when the poloidal oscillations were most clearly seen. This phase relation is a signature of propagating waves.

In order to examine the propagation of the wave energy we have calculated the Poynting flux of the waves,  $S = (1/\mu_0) \mathbf{E} \times \mathbf{b}$ , where  $\mu_0 = 4\pi \cdot 10^{-7} \text{ s}^2/\text{m}^2$ . Because of the noise-contaminated  $E_z$  amplitude

values, it is possible to calculate only an upper limit of the Poynting flux using the  $E_z$  data. Before calculation, we interpolated the electric field data to match the 6 s time resolution of the magnetic data. The calculated Poynting flux is displayed in Figure 5: the  $\mu$ ,  $v$ ,  $\phi$  components in the first three panels, and the total Poynting flux in the bottom panel. The large magnitude of the Poynting flux before  $\sim 1700$  UT was due, in large part, to the noise contamination in the  $E_z$  data, but it is clear that the flow direction of the energy flux was mainly in the  $-\mu$  direction, i.e., along magnetic field lines toward the southern ionosphere. After  $\sim 1700$  UT, when the toroidal waves dominated, the Poynting flux oscillated around zero in the three components. These results show that the DE 1 spacecraft, travelling inbound, observed propagating waves in the outer magnetosphere.

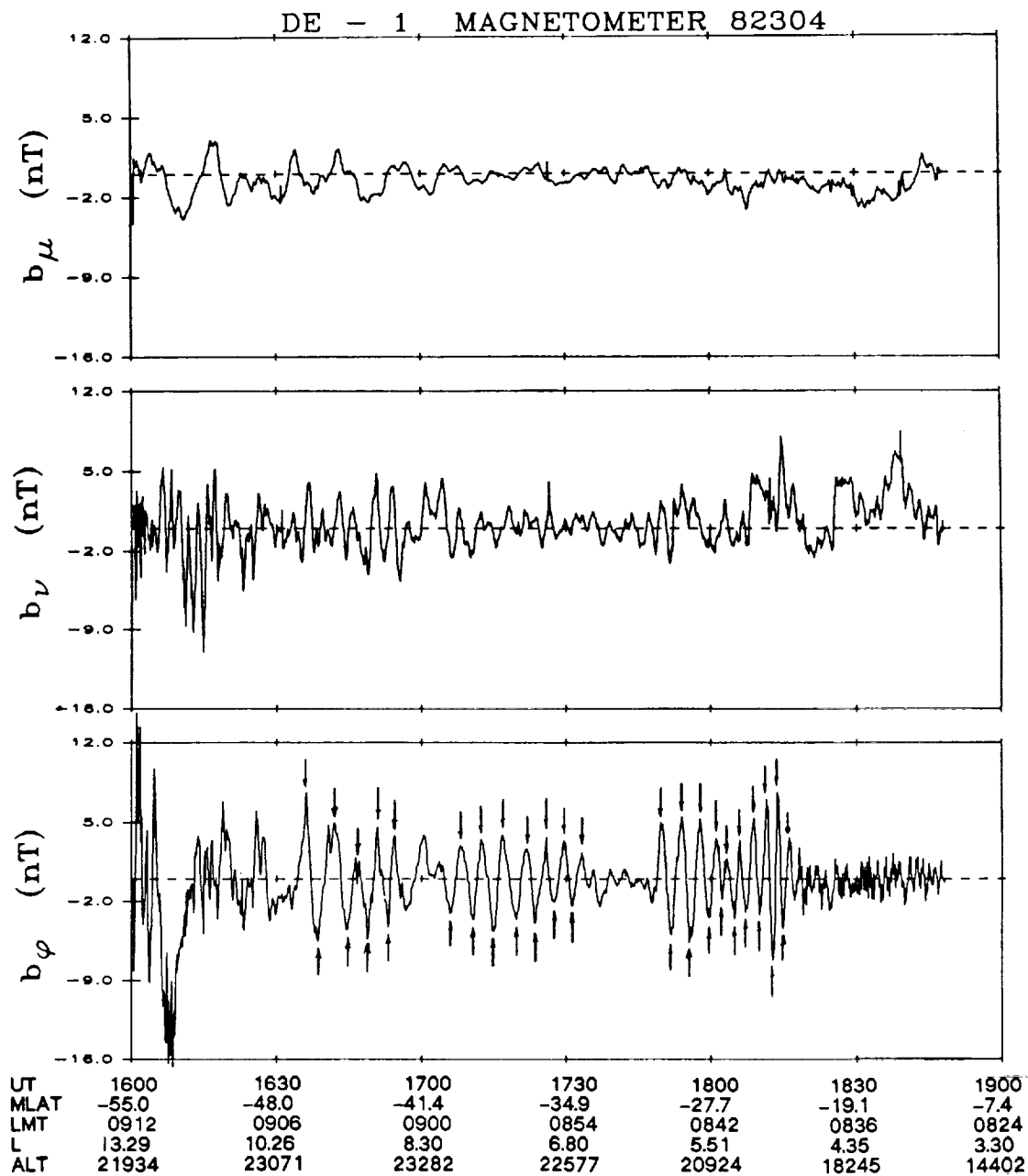


Fig. 3b. Magnetic field data in a field-aligned coordinate system with orthogonal unit vectors  $\mu$  (parallel to the background magnetic field), the transverse poloidal component  $v$ , and the azimuthal component  $\phi$ .

As it moved further into the magnetosphere, the spacecraft entered regions where magnetic field lines oscillated in the form of standing waves.

#### GROUND OBSERVATIONS

The DE 1 satellite trajectory was magnetically conjugate to western Canada during the interval of pulsation activity from 1600 UT to 1900 UT. Figure 6 shows the footprint of the DE 1 trajectory for the time interval being studied, and includes the locations of several Alaskan and Canadian magnetic observatories. The coordinates of the stations are summarized in Table 2. The ground magnetometer data are available for three components: the north-south component,

$H$  or  $X$ , with  $+H$  or  $+X$  pointing north, the east-west component,  $D$  or  $Y$ , with  $+D$  or  $+Y$  pointing east, and vertical component  $Z$ , with  $+Z$  downward. In this paper we will show the north-south component only. The available data have 1-min time resolution, with the exception of College search coil data which have 10-s resolution. The data are grouped into two sets. The first set (Figure 7) covers the period of 1300 UT to 2100 UT from the stations at Sachs Harbor (SAH), Cape Parry (CPY), Inuvik (INK), Fort Yukon (FYK), College (COL), and Talkeetna (TLK) and thus gives the magnetic field components for decreasing geomagnetic latitude and  $L$  values, approximately along a magnetic meridian. The second set of data is from Fort Smith (FSM), Fort Simpson (FSP), Norman Wells (NOW), and College (COL), which, from east to west, follow the auroral oval approximately (Figure 8).

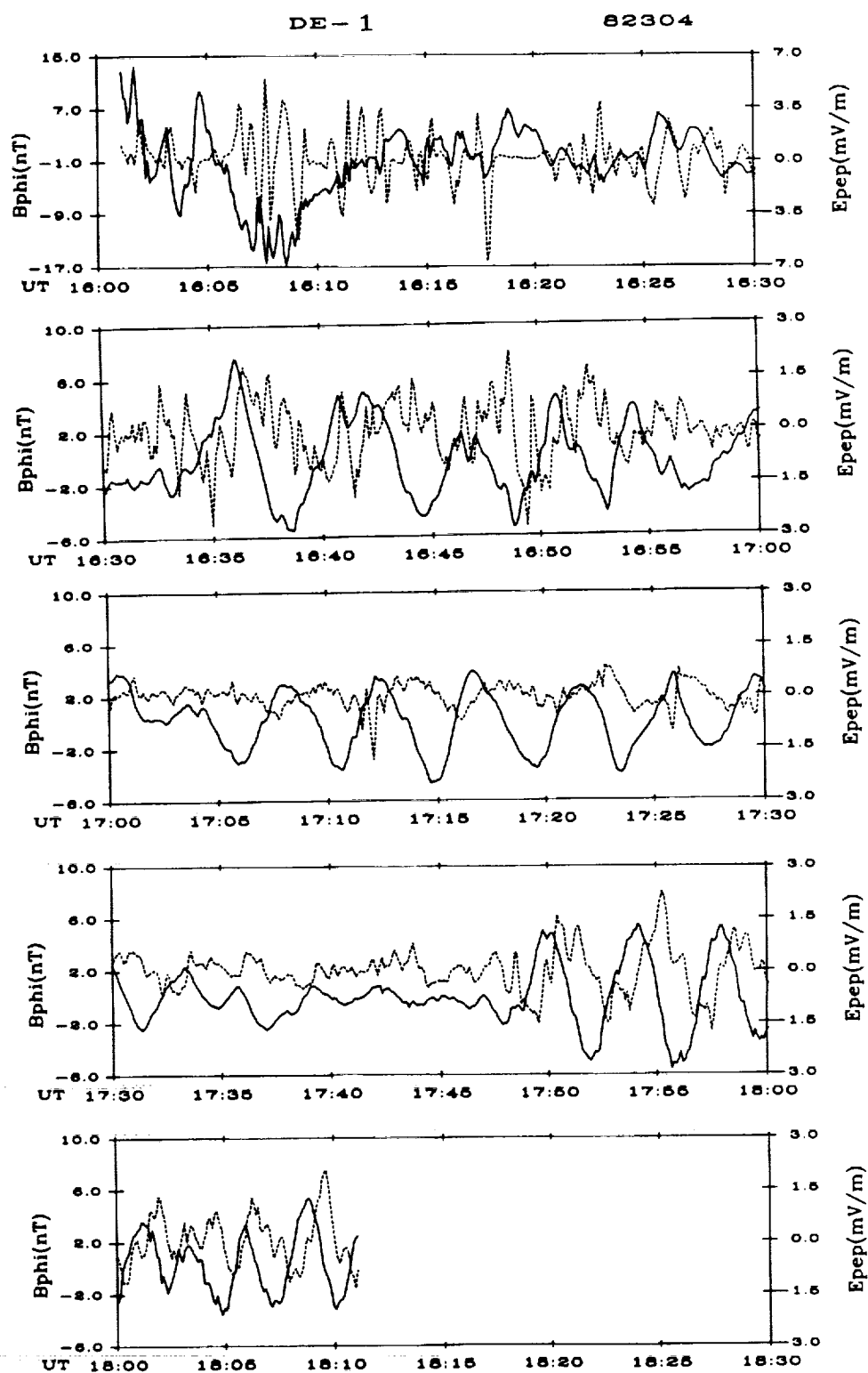


Fig. 4. Comparison between the azimuthal magnetic field variation,  $b_{\phi}$  (solid lines), and the variation of the spin-plane component of the electric field which is perpendicular to the magnetic field,  $E_{pep}$  (dashed lines).

The ground data show a series of magnetic disturbances. A signature which is probably associated with the sudden increase in solar wind pressure observed by ISEE 3 at  $\sim 1347$  UT is the small spike clearly seen in the  $H$  component (first vertical dashed lines in Figure 7 and 8) from all stations at  $\sim 1339$  UT. The second signature of magnetic disturbances occurred at about 1527 UT (marked by the

second vertical dashed lines in Figure 7 and 8), when negative bays were seen in the  $H$  components of all stations, especially in the INK station. Corresponding signatures were also evident in the east-west and the vertical components (not shown). These negative bays simultaneously observed in the  $H$  components were probably caused by a westward electrojet, the center of which developed above INK



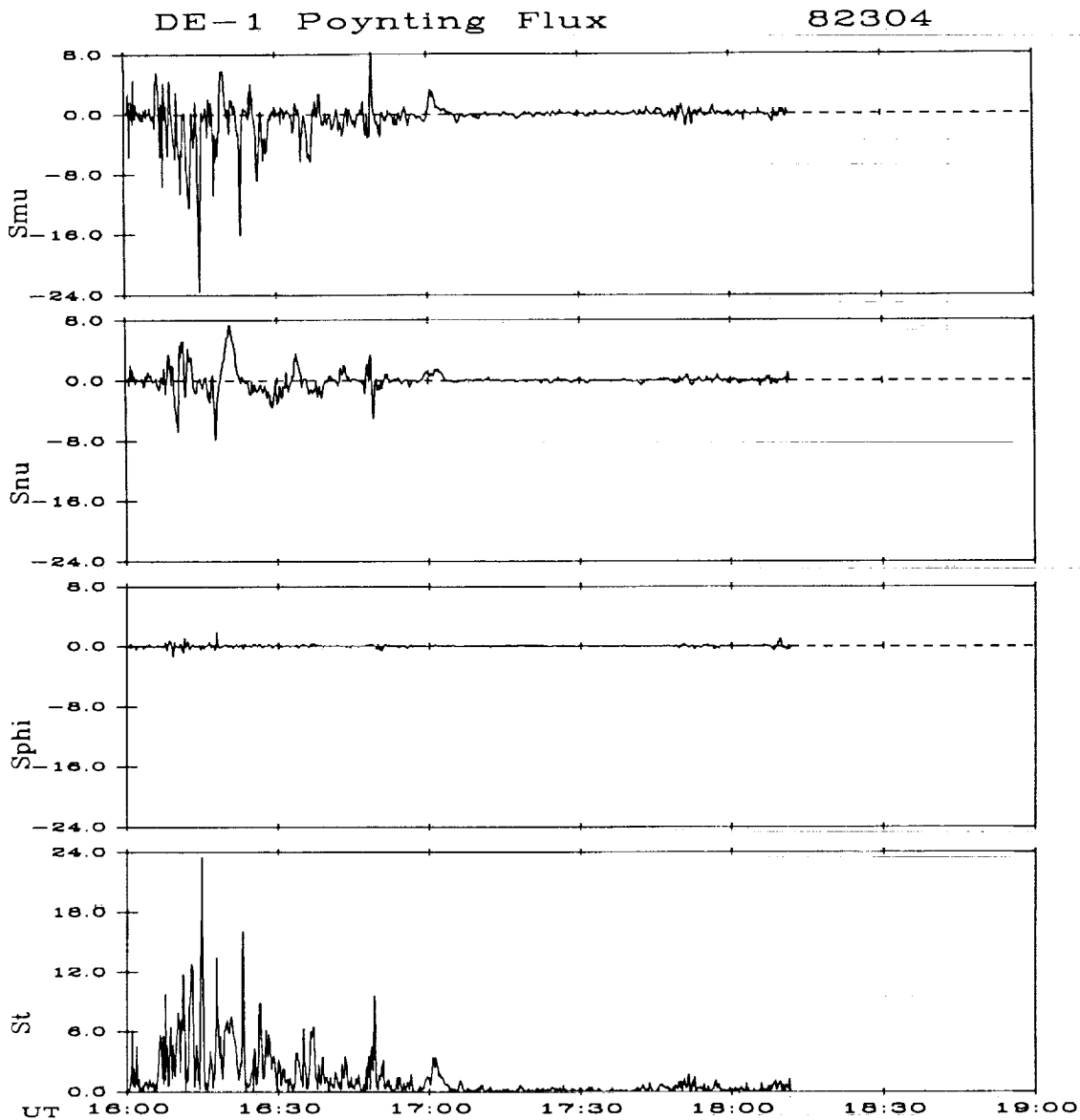


Fig. 5. The Poynting flux (in  $10^{-5}$  Watts/m<sup>2</sup>) for the interval 1600 to 1802 UT. The first three panels show the  $\mu$ ,  $\nu$ , and  $\phi$  components, and the bottom panel shows the total Poynting flux.

and thus reduced the  $H$  component of INK data most significantly. This electrojet also caused the  $Z$  components (not shown) of the stations to the north of INK (CPY and SAH) to increase forming positive bays, and those of the stations to the south of INK (FYU and COL) to decrease forming negative bays. This relatively weak westward electrojet seemed to be a precursor of much larger electrojets which occurred a few hours later. At about 1800 UT, large magnetic variations occurred, indicating development of a substorm. The signature was seen earlier in higher latitude (polar cap) stations. Figure 7 shows (marked by arrows) that the  $H$  component at SAH began to increase at about 1730 UT to a maximum of about 250 nT, then became negative at  $\sim 1843$  UT. A few minutes later, similar variations occurred at CPY (beginning at  $\sim 1735$  UT) and INK (beginning at  $\sim 1748$  UT). Stations at lower latitudes (FYU, COL, and TLK) observed only large decreases (negative bays) after 1800 UT. At College the negative bay developed most intensely.

To see magnetic pulsations more clearly, we display in Figures 9 and 10 the magnetic data which are used in Figures 7 and 8 but after

subtracting a 17 point (17 min) running average from the original data. Figures 9 and 10 show that magnetic pulsations began at all stations after the spikes at about 1339 UT which were associated with the solar wind pressure increase. The development of pulsations after 1339 UT is more clear at higher latitudes (Figure 9). The electrojet events described in the previous paragraphs seem to be associated with intensifications of ground pulsations. We have marked vertical lines and arrows in Figures 9 and 10, corresponding to the lines and arrows in Figures 7 and 8. Figures 9 and 10 show that, after  $\sim 1525$  UT, when small bays in  $H$  began at all stations, the pulsations intensified and the amplitude of the fluctuations became larger. Associated with the substorm development around 1800 UT, which was characterized by first eastward and then westward electrojets, another intensification of magnetic fluctuations was seen at each station, especially those at lower latitudes (FYU, COL, TLK, FSM, FSP, and NOW). The onset times of this intensification in each station seemed to coincide with the time when the station began to feel the effects of the eastward or westward electrojets.

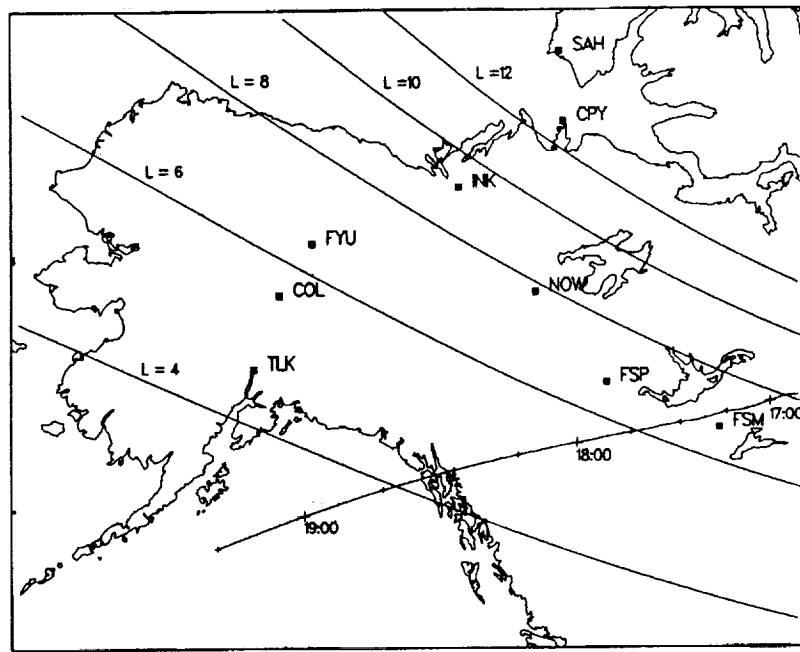


Fig. 6. A map indicating locations of the stations and the ionospheric footprint of the DE 1 trajectory for the time interval being studied.

TABLE 2. List of Station Coordinates

Station		$L$	Geomagnetic Latitude	Geomagnetic Longitude	Invariant Latitude
Sachs Harbor	(SAH)	16.99	77.3	268.0	75.96
Cape Parry	(CPY)	13.78	75.7	272.3	74.37
Inuvik	(INK)	9.39	72.7	264.9	70.95
Fort Yukon	(FYU)	6.60	69.2	253.8	67.09
College	(COL)	5.55	66.9	252.9	64.88
Talkeetna	(TLK)	4.82	62.2	258.6	62.90
Fort Smith	(FSM)	5.81	67.4	298.9	65.49
Fort Simpson	(FSP)	6.71	67.2	287.2	67.30
Norman Wells	(NOW)	8.00	69.4	276.9	69.30
College	(COL)	5.55	66.9	252.9	64.88

The waveforms observed at each station are not sinusoidal, implying that the waves consist of several frequency components. Fourier analysis was applied to the data to determine wave frequencies. Before performing the FFT, we calculated the time derivative of the original data to emphasize the short period variations. Since the data have 1-min resolution, the shortest period we could determine using Fourier methods is 120 s (8.3 mHz). For each FFT we took 128 points starting from 1600 UT. The results are listed in Table 3. The

frequency peak values in each component at each station are listed in the table in descending order of their power. In general, the power is larger for longer-period components.

While the waves observed at DE 1 have a narrow frequency band, the waves on the ground have a broader frequency range. At each station the magnetic pulsations consist of several frequency components, including those observed in space. For example, between 1630 UT and 1700 UT, DE 1 was traversing  $L$  shells of  $L \sim 10.3$  to

TABLE 3. Wave Frequencies at Ground Stations

Station		$L$	$H$ or $X$	D or Y Frequency, mHz	$Z$
Sachs Harbor	(SAH)	16.99	1.45, 2.0, 2.6, 3.2, 4.5, 5.5	2.0, 5.5	1.4
Cape Parry	(CPY)	13.78	1.4, 2.1, 3.0, 4.0, 4.7	1.9-2.5, 3.0, 3.8, 6.0	1.3, 2.4, 4.0
Inuvik	(INK)	9.39	2.3, 3.3, 4.4, 5.5	2.0, 2.9, 5.5, 4.0	1.3, 2.0, 3.0
Fort Yukon	(FYU)	6.60	2.0, 4.0, 5.5	5.5, 6.5, 3.7	2.0, 4.0, 5.3, 6.0
College	(COL)	5.55	5.5, 6.5, 2.0, 3.9, 3.2	5.5, 6.7, 3.7	3.7, 2.2
Talkeetna	(TLK)	4.82	5.5 - 6.5	5.6	
Fort Smith	(FSM)	5.81	3.7, 4.5, 2.2, 5.6	3.1, 3.7, 5.5, 2.0	3.1-3.8, 4.5
Fort Simpson	(FSP)	6.71	3.8, 4.4, 5.4, 1.9 - 2.3	6.6, 3.2, 5.4, 2.1, 3.7, 4.4	3.9, 2.0, 3.1, 5.4
Norman Wells	(NOW)	8.00	4.5-5.4, 6.6, ~ 2.0, 3.8	6.6, 5.5, 6.0, 2.0, 3.0, 3.7	4.5, 2.4, 3.0, 3.7

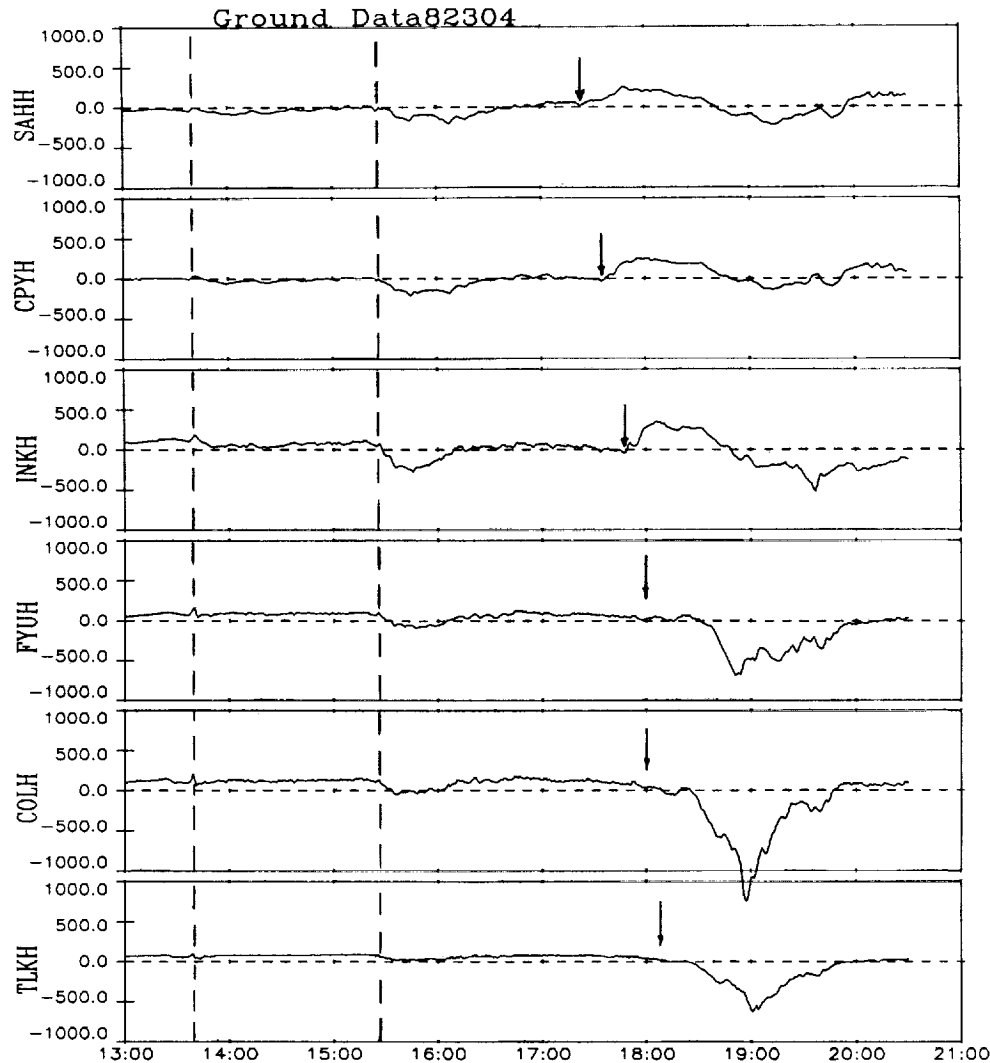


Fig. 7. The north-south component,  $H$ , of 1-min resolution magnetometer data for the period 1300 UT to 2100 UT from the stations at Sachs Harbor (SAH), Cape Parry (CPY), Inuvik (INK), Fort Yukon (FYU), College (COL), and Talkeetna (TLK), which are at decreasing geomagnetic latitudes and  $L$  values, approximately along a magnetic meridian.

8.3, and observed waves with increasing frequencies 2.2 to 5.5 mHz. These frequency components were also seen at the stations near the above  $L$  values, INK ( $L \sim 9.4$ ) and NOW ( $L \sim 8.0$ , see Table 3). Between 1700 UT and 1805 UT, DE 1 was traveling from  $L \sim 8.3$  to 5.3. The waves it observed were mainly at a frequency of 3.9 mHz. Similar frequencies (3.7–4.0 mHz) were observed at the stations near these  $L$  values, e.g., FSM, FSP, NOW, FYU, and COL. The last wave packet seen in space between 1805 and 1820 UT ( $L \sim 5.3$ –4.7) has a frequency of 6.5 mHz. This frequency component was also seen at COL ( $L \sim 5.6$ ) and TLK ( $L \sim 4.8$ ).

The time variation of the  $H$  and  $D$  components, measured by College search coils, is displayed in Figure 11 for the interval from 1600 UT to 1845 UT. Quasi-sinusoidal waves are seen in both components before 1800 UT. Fourier analysis of the data shows that frequency components at  $\sim 5.7$ –6.7 mHz (150–175 s period) consistently existed until about 1800 UT, when higher-frequency variations appeared and the longer-period waves gradually disappeared. The main frequency seen at the search coil data, about 6.5 mHz (154-s period), was very close to that observed by DE 1 between 1805 and 1820 UT. Hodograms produced using the above search coil data filtered in a frequency band between 5 and 10 mHz (not shown)

showed that the wave was left-hand polarized throughout the 2-hour interval (1600–1800 UT), which was in the same direction as the 6.5-mHz wave in space. Figure 11 shows that after 1800 UT the fluctuations began to intensify, and the waveform became more irregular; shorter-period (less than 100 s) fluctuations appeared. This change is coincident with the development of the large negative bay seen at College. We note that a similar change was observed at DE 1: At 1815 UT the 150-s wave observed by DE 1 decayed rapidly, and shorter-period waves (37 mHz) appeared.

#### DISCUSSION

We have observed a ULF wave event during a magnetically disturbed interval. The onset of pulsations on the ground was coincident with a sudden increase in the solar wind velocity and solar wind pressure at  $\sim 1345$  UT. Another change in solar wind parameters at about 1530 UT (a northward turning of IMF  $B_z$ , and intensification of the fluctuations of the solar wind dynamic pressure) was apparently associated with the second intensification of Pi pulsations on the ground which was coincident with small negative bays in the  $H$  components. Field line oscillations observed by DE 1 in space were

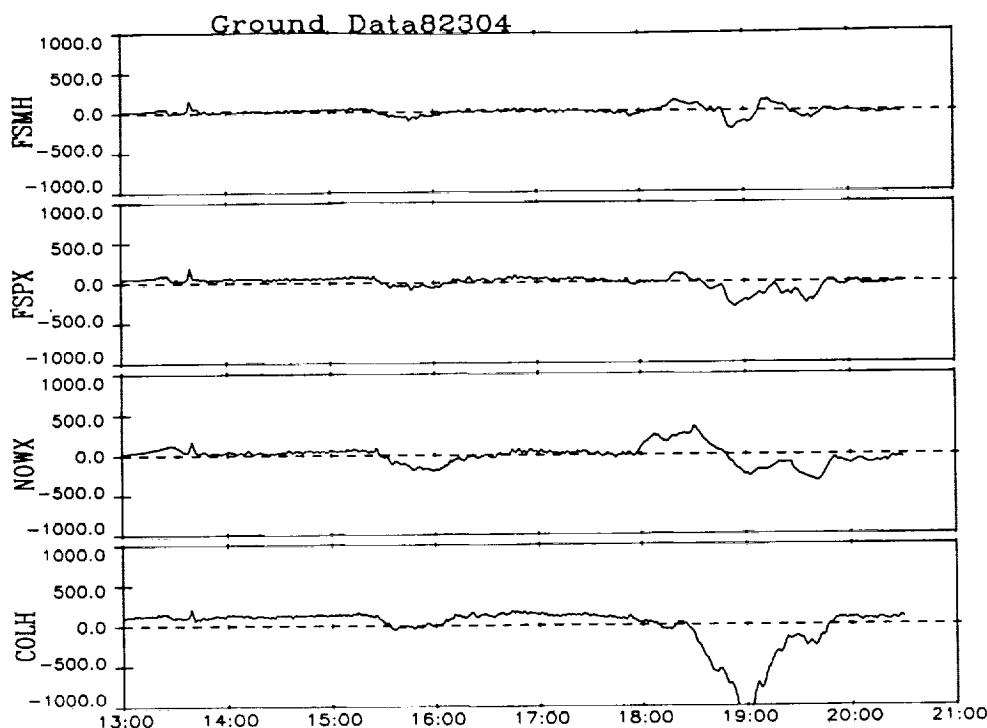


Fig. 8. The same as Figure 7, but for stations Fort Smith (FSM), Fort Simpson (FSP), Norman Wells (NOW), and College (COL), which, from east to west, follow the auroral oval approximately.

probably also associated with the above intensification of variations in the solar wind parameters around 1530 UT.

It has been reported that a sharp increase in solar wind dynamic pressure may initiate ringing of the magnetosphere [cf. *Sibeck et al.*, 1989]. *Southwood and Kivelson* [1990] have shown that a pressure perturbation at the magnetospheric boundary can excite fast mode and transverse mode eigenoscillations in the magnetosphere. The coincidence between the pulsation intensifications and the changes in the solar wind dynamic pressure in this event suggests that the magnetic pulsations were first excited by the increase of the solar wind dynamic pressure at  $\sim 1345$  UT (the first vertical dashed lines in Figure 9), and another burst of pulsations at 1530 UT (the second vertical dashed lines in Figure 9) was the response of the magnetosphere to the intensification of the solar wind perturbation. DE 1, which entered the magnetosphere shortly after 1600 UT, observed the ringing of the magnetosphere.

RIMS and EICS data indicate that DE 1 might have entered a closed field line region from an open field line region at  $\sim 1606$  UT. On entering the closed field line region, DE 1 observed a 110-s wave mainly in the poloidal component ( $b_v$ ). The antiphase relation between  $b_v$  and  $E_z$  indicates that the wave was propagating. A Poynting flux calculation shows that the waves seen in the outer magnetosphere before 1700 UT ( $L > 8.3$ ) had a significant component propagating along the ambient field lines toward the southern hemisphere.

Longer-period ( $\sim 650$  s) compressional oscillations with decaying amplitude were seen from the beginning of the available DE 1 data until about 1715 UT. The compressional waves preceded the transverse oscillations and lasted for more than one hour. *Cahill et al.* [1990] reported a toroidal Pc 4 wave preceded by rapidly damped compressional oscillations which were excited by a world wide storm sudden commencement. They suggested that the compressional pulsations were evidence of global cavity resonance oscillations and had coupled to the transverse oscillations. In our event the compres-

sional oscillations might have been the oscillations of the magnetosphere in response to the variations of the solar wind velocity and pressure. The main frequency component ( $\sim 1.5$  mHz) is much lower than the toroidal oscillations seen by DE 1 after 1630 UT. However, Fourier analysis of the waves between 1600 UT and 1700 UT shows that there are minor peaks at  $\sim 2.9$  and  $4.5$  mHz. It is possible that these compressional oscillations with frequencies matching the eigenfrequencies of magnetic field lines at lower  $L$  shells coupled with toroidal modes and produced strong azimuthal oscillations which were seen by DE 1 after 1630 UT.

It is interesting to note that the period of the azimuthal oscillations decreased continuously with  $L$  values in the first wave packet (1630 - 1700 UT). It seems that in this event adjacent magnetic shells in the outer magnetosphere region ( $L = 10.3 - 8.3$ ) rang at their own eigenperiods with little interaction. This phenomenon has been observed previously (see, for example, the third event in the work by *Lin et al.* [1986]), and was commonly seen in AMPTE CCE observations [cf. *Engbreton et al.*, 1986a; *Anderson et al.*, 1990]. The continuous variation of the wave period with  $L$  values suggests that the sources of the waves, presumably the variation of the solar wind dynamic pressure at the magnetopause, had a broad frequency bandwidth. Such sources may drive harmonic oscillations over an extended radial distance with each field line resonating at its Alfvén resonance frequency [*Hasegawa et al.*, 1983]. This kind of source is likely to be spatially localized and have a large azimuthal wave number. In this case the global eigenmodes do not occur and the compressional signal decays away from the boundary [*Southwood and Kivelson*, 1990], as is observed in this case.

The azimuthal waves can be divided into several wave packets which correspond to different plasma regions: before 1655 UT, ions streamed along field lines predominantly in the direction of magnetic field lines. From 1655 UT to 1745 UT, field-aligned streaming ions still dominated but traveled in both directions. Soon after 1740 UT, DE 1 started to see isotropic ion distributions, and at about 1753 UT

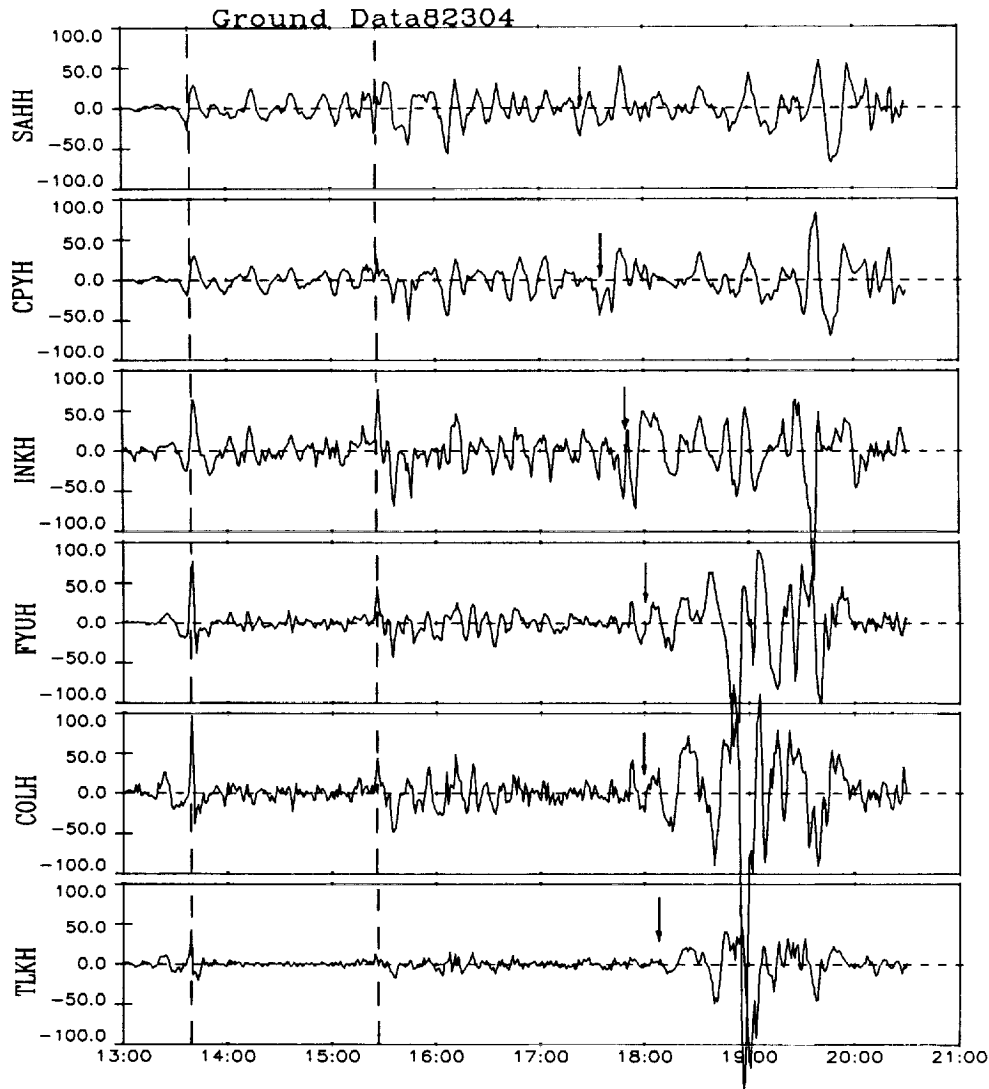


Fig. 9. Variations of the  $H$  component displayed in Figure 7 after subtracting a 17 point (17 min) running average from the original data.

the satellite observed a significant plasma density gradient, which indicates that the spacecraft entered the plasmasphere. Azimuthal pulsations were observed by DE 1 on both sides of the plasmopause. The wave packet observed before DE 1 entered the plasmasphere (between 1705 UT and 1740 UT) had a nearly constant period ( $\sim 256$  s). Considering that the wave source may be broadband and each ringing field line oscillates at its own Alfvén resonance frequency, the constant wave period is consistent with the existence of a plasma density gradient near (outside) the plasmopause region. Theoretical models of the variation of the eigenfrequency of toroidal oscillations (see, for example, Figure 9 of Yumoto and Saito [1983]) predict a sharp increase in the wave frequency at the plasmopause. This was not observed in our event; instead, a transition between two wave packets was observed near the plasmopause crossing (1740 - 1750 UT).

To examine the changes of the wave period with  $L$  shells, we plotted the observed period versus  $L$  values in Figure 12a. In creating this diagram we took three intervals (1635 - 1700 UT, 1703 - 1735 UT, and 1745 - 1820 UT) when wave signatures were clear, measured the time difference between two successive maxima (or two successive minima), and then took this value as the wave period at the midtimes between the two maxima (or the two minima). The maxima and

minima we used are indicated by arrows in Figure 3b. The error of such measurements will not exceed 30 s per cycle. The periods obtained were then plotted in Figure 12a with plus signs. The figure shows continuously decreasing periods with decreasing  $L$  in the outer magnetosphere ( $L > 8.5$ ) and in the plasmasphere region ( $L < 5.8$ ), but in the region just outside the plasmopause ( $L \sim 6.7 - 7.9$ ), the period varied around 250 s.

We also show in Figure 12a three lines which represent variations of the eigenperiod of field lines versus  $L$ . The eigenperiod was calculated as [Orr and Matthew, 1971]

$$T = 0.05881 L^4 (n_0 / kC)^{1/2} \quad (1)$$

where  $n_0$  is the equatorial mass density. The value  $kC$  is calculated using the formulae developed by Taylor and Walker [1984] for toroidal oscillations in a dipolar geomagnetic field with infinite ionospheric conductivity boundary condition. The plasma density distribution along a field line is assumed to be  $n = n_0 (r_0 / r)^m$ , where  $r_0$  is the geocentric distance to the equatorial crossing point of the field line considered and  $r$  is the geocentric distance to a point on the field line. Inside the plasmopause, the density index  $m$  is chosen to be equal to 3, and

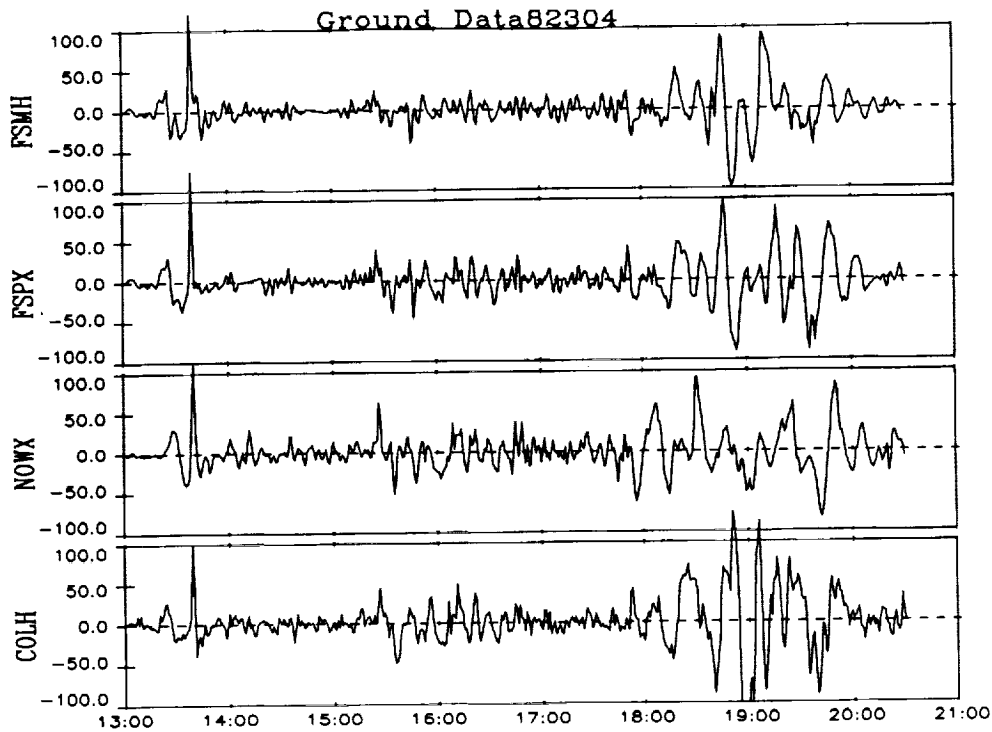


Fig. 10. Variations of the  $H$  component displayed in Figure 8 after subtracting a 17 point (17 min) running average from the original data.

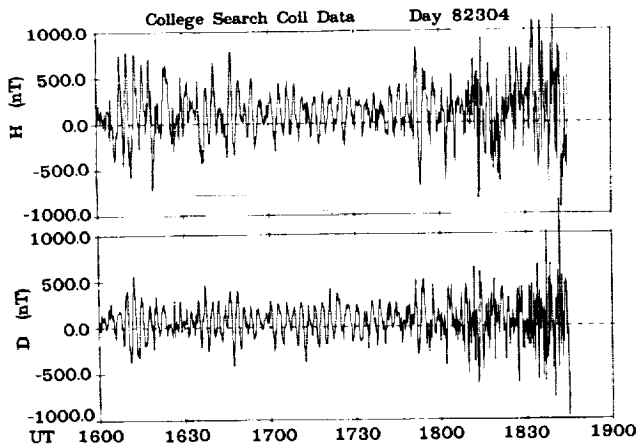


Fig. 11. Search coil magnetometer data from College, Alaska, at 10-s resolution. The search coil responds to  $dB/dt$ , so suppresses longer period components. (a) North-south component  $H$ , and (b) East-west component  $D$ .

$$kC = (\pi/S_0)^2 [1 - (0.0980S_0^2 - 0.0077S_0^4 + 0.0003S_0^6)] \quad (2)$$

where  $S_0 = 2\sin\Lambda$ , and  $\Lambda$  is the invariant latitude which can be calculated from  $L$  values using  $L = 1/\cos^2\Lambda$ . Outside the plasmopause  $m = 4$ , and

$$kC = (\pi/S_0)^2 [1 - (0.0653S_0^2 - 0.0026S_0^4)] \quad (3)$$

In the calculation we have assumed that the pulsations were fundamental mode oscillations, and took the equatorial density to be  $55 \text{ amu/cm}^3$  for  $L$  between 4.8 and 6.0;  $9 \text{ amu/cm}^3$  for  $L$  between 6.4 and 8.0; and  $1.5 \text{ amu/cm}^3$  for  $L$  between 8.5 and 9.8 in order to fit the data in each interval. It is shown from the figure that for the outer

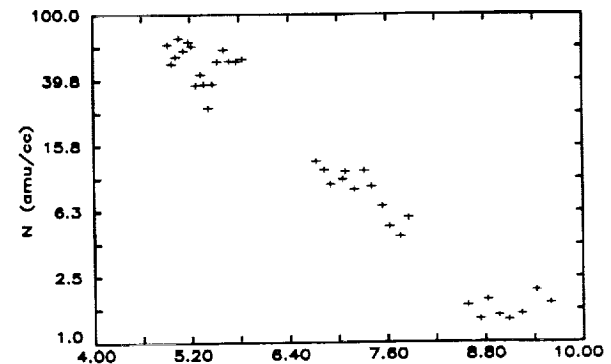
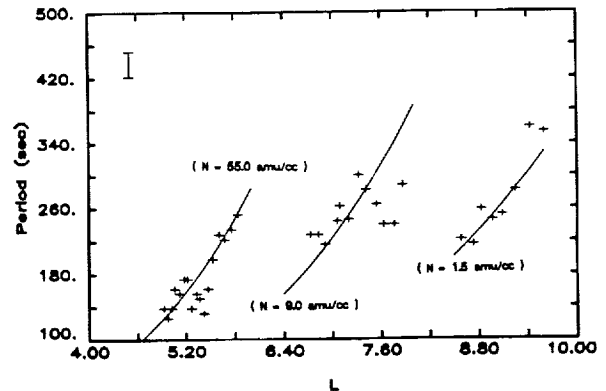


Fig. 12. (a) Wave periods observed by DE 1 versus  $L$  value. The periods (plus sign) were measured during three intervals (1635 - 1700 UT, 1703 - 1735 UT, and 1745 - 1820 UT) when wave signatures were clear. The three solid lines represent variations of calculated eigenperiods of field lines versus  $L$ , assuming that the pulsations were fundamental mode. (b) Equatorial mass densities derived from the observed period plotted as a function of  $L$ .

magnetosphere ( $L > 8.5$ ), the calculated periods assuming a fixed equatorial density basically agree with the observed periods within the error range. For the region inside the plasmasphere ( $L < 5.8$ ) the fit is reasonably good, while for the region outside the plasmasphere (between  $L \sim 6$  and 8), the fit is quite poor, which suggests that the density in this region was not a constant.

In Figure 12b we plotted the equatorial mass density derived from the observed period versus  $L$  using the same model, and again assuming the waves were fundamental oscillations. The figure shows that the equatorial mass density was nearly constant ( $1-2 \text{ amu/cm}^3$ ) in the outer magnetosphere; from  $L \sim 8$  to 6 the density gradually increased from  $\sim 4$  to  $\sim 12 \text{ amu/cm}^3$ , while inside the plasmasphere ( $L < 5.8$ ) the calculated plasma density was fluctuating with an average of  $\sim 52 \text{ amu/cm}^3$ . For the region far outside the plasmapause the assumption of fundamental mode oscillation seems to be justified, as we obtain a reasonable equatorial mass density. Immediately outside the plasmapause we obtain a gradual density ramp. For the region inside the plasmapause, this assumption again gives reasonable results, but we cannot be sure that the waves were in the fundamental mode. If they were not, the equatorial density could be higher. For example, at  $\sim 1812 \text{ UT}$  DE 1 was at  $L \sim 5$  and at  $\sim 25^\circ$  geomagnetic latitude. It observed a toroidal wave of 154-s period. A comparison of  $b\phi$  and  $E_{\text{perp}}$  (Figure 4) shows that  $b\phi$  led  $E_{\text{perp}}$  by  $90^\circ$ . This phase relation is consistent with that of both fundamental and second harmonic oscillations for a spacecraft at high latitudes [Cahill et al., 1986]. If the wave was the second harmonic, then the equatorial density should be about  $140 \text{ amu/cm}^3$  to produce a 154-s oscillation.

The phase relation between  $b\phi$  and  $E_{\text{perp}}$  with  $b\phi$  leading  $E_{\text{perp}}$  by  $90^\circ$  for the four toroidal wave packets indicates that the waves were standing along magnetic field lines. We have noted that during the second wave packet (1700–1740 UT),  $E_{\text{perp}}$  declined to  $\sim 0.1 \text{ mV/m}$  in amplitude. This is unexpected, since the spacecraft was at  $\sim 41^\circ$  to  $\sim 32^\circ$  geomagnetic latitude ( $L \sim 8.3$ – $6.3$ ) and there are no nodes of  $E_{\text{perp}}$  at such high latitudes along field lines oscillating in the form of standing waves for the first few harmonics [cf. Cummings et al., 1969]. We may estimate roughly the comparison of  $E_{\text{perp}}$  and  $b\phi$  using a model by Allan and Knox [1979] which considers finite conductivities of the ionosphere. First, we do the comparison for the  $E$  and  $b$  field at 1755 UT. The spacecraft at that time was at  $\sim 29^\circ$  geomagnetic latitude and at  $L \sim 5.7$ . The observed  $b\phi$  was about 5.5 nT in amplitude. From Figure 4 of Allan and Knox [1979], which is for the fundamental standing wave at  $L = 4$  with conductivities of 10 S at both ends of the field line, the oscillation with 5.5 nT would produce an  $E_{\text{perp}}$  component with an amplitude of  $\sim 5.5 \text{ mV/m}$ , which is about 2 times larger than the observed  $E_{\text{perp}}$  value. At 1715 UT the spacecraft was at  $\sim 38^\circ$  geomagnetic latitude and at  $L \sim 7.5$ . For the observed  $b\phi$  (about 4.5 nT) the model produces an  $E_{\text{perp}}$  value

of about 3 mV/m, which is more than ten times larger than the observed  $E_{\text{perp}}$  value. Note that the model of Cummings et al. [1969] produces even larger  $E_{\text{perp}}$  values (see also Cahill et al. [1986]). Although the model of Allan and Knox we used is for  $L = 4$ , the observed  $E_{\text{perp}}$  for the wave packet between 1700 UT and 1740 UT is obviously much less than what field line resonance theory predicts and thus is puzzling.

Wave signatures on the ground are more complicated, containing more frequency components than those observed by DE 1. Although the spacecraft crossed magnetic shells at points roughly conjugate to several stations, the waves seen most strongly in space were often not the strongest signals seen on the ground. The broadband nature of the ground observations suggests that the ground stations also detected oscillations of the adjacent field lines, and during magnetically active periods, the effects of the adjacent field lines became stronger. This "spatial integration" of pulsation signals by ground magnetometers has been discussed in detail by Poulter and Allan [1985].

We note that the major frequencies of pulsations at ground stations were latitude dependent. Figure 9 shows, for example, that periods of pulsations after 1530 UT from stations SAH to TLK decreased with magnetic latitude and thus with  $L$  values. This can also be seen from Table 3. The first (the strongest) frequency component of  $H$  or  $X$  components for the first six stations tends to increase with decreasing  $L$ . However, the frequency components seem to remain nearly constant for more than 1 to 2 hours at each station, while the period of the waves seen in space decreased during this interval. This suggests that the changing periods seen in space by DE 1 were clearly  $L$ -related and not temporally varying. College search coil data, which have 10-s resolution and suppressed long-period components, have shown that magnetic field lines at College station ( $L = 5.6$ ) had been oscillating for about 2 hours at 6.5 mHz, which was very close to the frequency observed by DE 1 when the spacecraft moved near the nominal  $L$  shell where College is located. DE 1 crossed  $L = 5.6$  at about 1758 UT when it saw a wave packet at  $\sim 260$ -s period weakening, and at a slightly later time, saw another wave packet with a period of  $\sim 150$  s (6.5 mHz). The latter is probably the one we saw the College data, and they are both left-handed polarized. The above observations support the idea that magnetic shells in the magnetosphere were oscillating independently while being driven by a broadband source. DE 1, traversing a large range of  $L$  shells, observed field lines oscillating at their eigenfrequencies, and the coupling between adjacent oscillating shells seems to be weak.

The small negative bays in  $H$  components seen at 1527 UT at ground stations are believed to be caused by a westward electrojet in the ionosphere. The associated bursts of the pulsations were seen to propagate westward. In Figure 13 we compare the signals between 1500 UT and 1800 UT recorded at Fort Simpson (solid line) and at

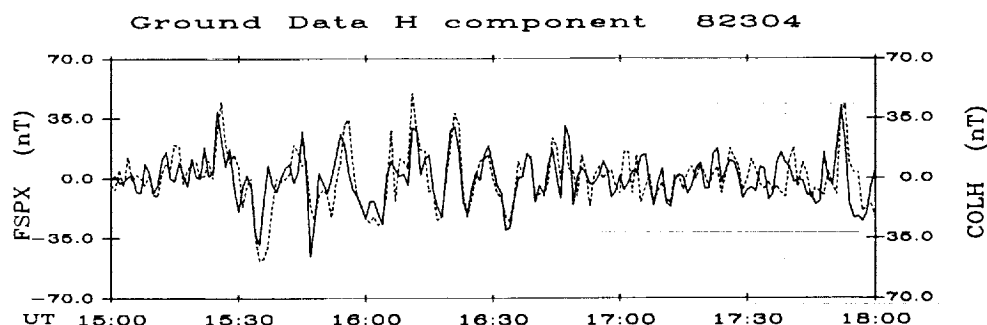


Figure 13. Comparison between north-south components of magnetic field variations at Fort Simpson (solid line) and College (dashed line).

College (dashed line) which are about  $34^\circ$  apart in longitude. The signal at FSP is seen to lead that of COL which means that the waves propagated westward. The time difference is not more than 1 min, the time resolution of the data. The two stations are at about  $64^\circ$  geographic latitude and are separated by about 1660 km. Thus the westward velocity of the wave structure was at least 27 km/s.

The substorm signatures on the ground (starting at the times marked by arrows in Figure 7) have been associated with the southward turning of IMF  $B_z$ . By examining geomagnetic indices  $AU$  and  $AL$  (shown in Figure 14 along with  $AE$  index) and geomagnetic records in Figure 7 and 8, it seems that the substorm in this study developed in two steps, a growth phase and an expansion phase. During the growth phase, between  $\sim 1730$  UT and 1826 UT, the eastward Hall current developed at higher latitudes (invariant latitudes  $> 69^\circ$ ) at SAH, CPY, INK, and NOW, and the westward Hall current developed at lower latitude at COL, with the vortex center near FYU ( $INV \sim 67^\circ$ ). Starting from  $\sim 1740$  UT, DE 1 observed a large increase in  $dB\theta$ , indicating an increased stretching out of field lines during this growth phase. The expansion phase (after about 1826 UT as seen from  $AL$  or  $AE$  indices) was manifested by the onset of a sharp intensification of the westward electrojet at COL. During this expansion phase, intensifications of long-period magnetic fluctuations were seen at all stations (Figures 9 and 10). However, such strong intensifications of pulsations were not observed in space. Instead, at about 1820 UT the last wave packet with 150-s period decayed rapidly. This may imply that the large fluctuations seen relatively worldwide on the ground were caused by the variation of an ionospheric current system which closed itself mainly on the ionosphere and thus had little effects on the current observed at DE which was in the conjugate magnetosphere.

### SUMMARY

The pulsations we studied apparently were excited by variations of solar wind dynamic pressure and magnetic field. A sudden increase in the solar wind velocity and solar wind pressure at  $\sim 1345$  UT and an intensification of fluctuations in the solar wind parameters at  $\sim 1530$  UT initiated two bursts of pulsations on the ground; a southward turning of IMF  $B_z$  at  $\sim 1740$  UT, which apparently triggered a

substorm, excited another burst of long-period pulsations on the ground but not seen in space.

In response to the above solar wind variations, magnetic shells in the magnetosphere resonated at their own eigenfrequencies. DE 1, traveling inbound across a large range of  $L$  shells, thus observed azimuthal field line oscillations with periods decreasing with  $L$  values. The oscillating  $L$  shells seemed to interact very little with each other since the period changes occurred on closely adjacent field lines. The toroidal oscillations were preceded by decaying compressional waves seen in the outer magnetosphere. The compressional waves might have coupled with the transverse oscillations, transferring the energy to the resonating field lines.

Moving inbound, DE 1 appears to have entered a closed field line region from an open field line region at about 1619 UT and  $L \sim 11.2$ . On entering the closed field line region DE 1 observed propagating waves which had a strong poloidal component with a period of 110 s. The waves propagated along the ambient field lines toward the southern hemisphere. Azimuthal pulsations were observed by DE 1 on both sides of the plasmapause density gradient. The observed wave period before DE 1 entered the plasmasphere suggests that there was a gradual plasma density gradient just outside the plasmapause.

Pulsations on the ground were very irregular in contrast to those observed in space which were quasi-sinusoidal. The ground signals observed by the stations in regions conjugate to the path of DE 1 contained more frequency components than those observed by DE 1 but included those frequencies observed by DE 1 at the corresponding  $L$  shell. The broadband nature of the ground pulsations may have been the effect of the magnetometer sensing the oscillations of the adjacent field lines. The  $L$ -dependent but roughly constant major frequencies of pulsations at ground stations justified that the changing periods seen in space by DE 1 were  $L$ -related and not temporally varying.

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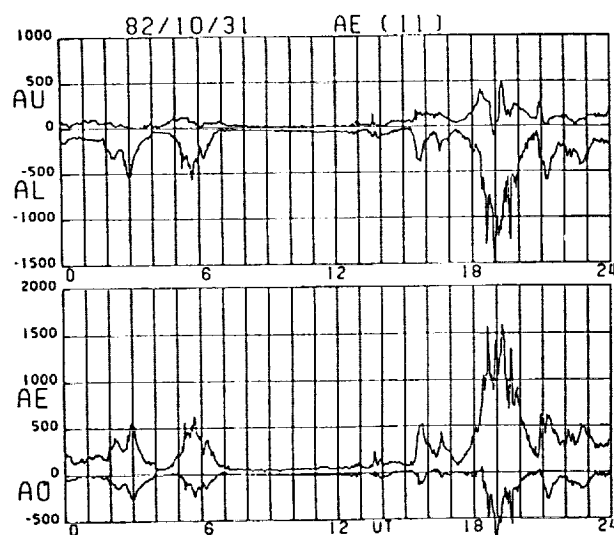


Figure 14. Geomagnetic indices for October 31, 1982. The upper panel shows the  $AU$  and  $AL$  indices. The lower panel shows the  $AE$  and  $A_0$  (defined as  $(AU + AL)/2$ ) indices.



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